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# First Order Fire Effects Model: FOFEM 4.0, User's Guide



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## Research Summary

A First Order Fire Effects Model (FOFEM) was developed to predict the direct consequences of prescribed fire and wildfire. FOFEM was designed for application to most areas of the United States. First order fire effects are the immediate or direct results of a fire. FOFEM computes duff and woody fuel consumption, mineral soil exposure, fire-caused tree mortality, and smoke production for many forest and rangeland ecosystems. Quantitative results from many fire effects studies were summarized for inclusion into the model. FOFEM contains a fire effects calculator to predict the effects of a fire from the burning conditions, and a prescribed fire planner to compute the burn conditions necessary to achieve a desired effect. Default input values are derived from fuel models provided for natural and activity fuels by many forest cover types. The model is implemented in a computer program available for use on a PC or Data General computer.



To obtain a current version of the FOFEM software, contact the authors at the Intermountain Fire Sciences Lab, (406) 329-4800, or P.O. Box 8089, Missoula, MT 59807.

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# First Order Fire Effects Model: FOFEM 4.0, User's Guide

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## Introduction

FOFEM—A First Order Fire Effects Model—is a computer program that was developed to meet needs of resource managers, planners, and analysts in predicting and planning for fire effects.

Quantitative predictions of fire effects are needed for planning prescribed fires that best accomplish resource needs, for impact assessment, and for long-range planning and policy development. We have developed the computer program FOFEM to meet this information need.

Much fire effects research has been conducted, but the results of this research have been somewhat difficult to apply. This is in part because fire effects research has tended to be empirical, and thus limited in applicability to situations similar to those under which the research was conducted. Additionally, fire effects research results have not previously been assembled in a common format that is easily accessed and used, but rather have been scattered in a variety of journals and publications.

In developing FOFEM, we have searched the fire effects literature for predictive algorithms useful to managers. These algorithms have been screened to evaluate their predictions over a range of conditions. We also determined the conditions under which each is best suited to use by examining the documentation of these algorithms. Thus, a major internal component of FOFEM is a decision key that selects the best available algorithm for the conditions specified by a user.

In addition to selecting appropriate algorithms for users, we have also attempted to make these algorithms simple to apply. This has been done by incorporating the algorithms in an easy-to-use, menu-driven computer program. Realistic default values, documented in detail in this guide, have been provided for many inputs, minimizing the data required. These defaults were derived from a variety of research studies. Any of these default values can be overridden by the user, allowing the use of this program at different levels of resolution and knowledge.

We anticipate that FOFEM will be useful in a variety of situations. Examples include: setting acceptable upper and lower fuel moistures for conducting prescribed burns; determining the number of acres that may be burned on a given day without exceeding particulate emission limits; assessing effects of wildfire; developing timber salvage guidelines following wildfire; and comparing expected outcomes of alternative actions.

FOFEM is available for IBM compatible PC's and for Forest Service Data General minicomputers.

## Overview

First order fire effects are those that concern the direct or immediate consequences of fire. First order fire effects form an important basis for predicting secondary effects such as tree regeneration, plant succession, and changes in site productivity, but these long-term effects generally involve interaction with many variables (for example, weather, animal use, insects, and disease) and are not predicted by this program. Currently, FOFEM provides quantitative fire effects information for tree mortality, fuel consumption, mineral soil exposure, and smoke. Future versions will also include soil heating and potential for successional change, as quantitative models become available.

FOFEM is national in scope. It uses four geographical regions (fig. 1): Pacific West, Interior West, North East, and South East. Forest cover types provide an additional level of resolution within each region. Geographic regions and cover types are used both as part of the algorithm selection key, and also as a key to default input values.

FOFEM provides two fundamental kinds of output—fire effects predictions, and fire planning recommendations. Both use the same underlying algorithms, but in the prediction mode the user enters preburn and burn-time conditions and the program computes the expected fire effects. In the planning mode, the user enters desired fire effects, and the program calculates a range of conditions that might be expected to produce these effects.

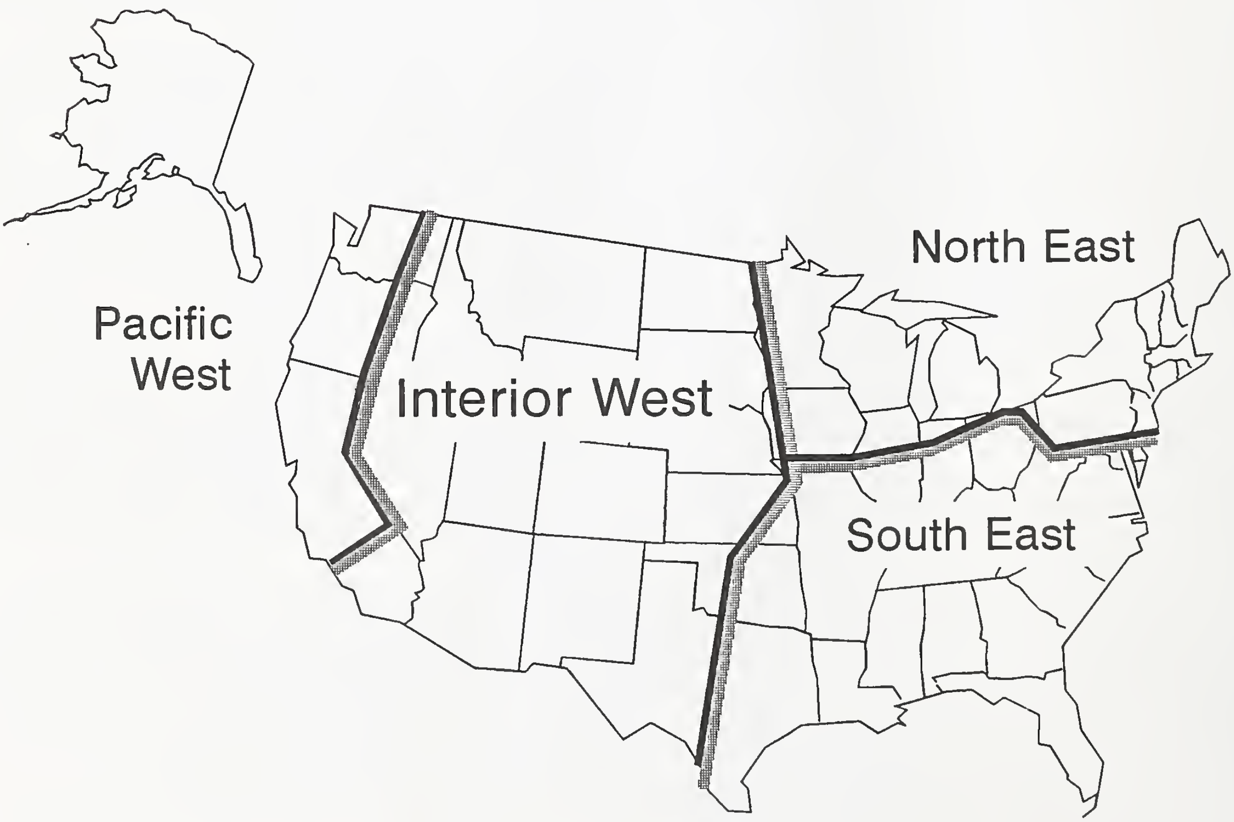


**Figure 1**—The four geographical regions used in FOFEM.

## Modeling Approach

In developing the decision key to select algorithms, we were guided not only by the conditions under which an algorithm was developed, but also by a need to develop a model without sharp discontinuities or inconsistencies. This made algorithm selections in some cases a "judgment call," and it also led to the exclusion of some algorithms that may have performed well but in very restricted situations, or that require inputs not easily available to managers. The Bibliography in this user's guide includes all publications that were considered in developing FOFEM, whether or not FOFEM actually incorporates their results. Sources for algorithms actually used in the program are documented in appendix B. The decision key is summarized in appendix C.

## Installing FOFEM

The FOFEM program and associated input files are available for implementation on IBM-compatible PC's and on the Forest Service Data General (DG) minicomputer. Information on these programs by hardware platform is as follows.

### IBM-Compatible PC

To install FOFEM on your PC you must have at least 1 Mbyte available on your hard disk and 640 Kbyte RAM. If you are using a 286, 386, or older 486 and do not have a math co-processor you will need to request a special version of FOFEM. The program works best on a 386/486 PC or better machine with DOS version 3.0 or greater, but should execute on a 286 if desired. Six files are included on a 1.44 Mbyte 3-½ inch floppy disk for implementation on the PC. These files and their bytesize are described below:

FOFEMSPP.DAT—Contains tree species information by regions (2938)
FOFEMCOV.DAT—Contains cover types and their attributes (8478)
FOFEMFUE.DAT—Contains fire effects fuel models (23743)
HELP.TXT—Contains help text (37840)
FOFEM.EXE—Executable program (445410)—NOT ASCII
READ.ME—A description file

To install on your PC, first create a new directory on your hard disk labeled FOFEM (DOS > MKDIR FOFEM). Then navigate to that directory using the CD FOFEM command in DOS, and type the DOS command > COPY A:*.* C: This will copy all files on the floppy onto the hard disk. This assumes that the FOFEM floppy was entered into the A: drive on the computer. Change the A: to B: if the B: drive was used. To execute the program, simply type the word FOFEM at the DOS prompt.

If you are running Windows, you will need to go to DOS to run FOFEM. You may need to exit Windows before running FOFEM if you run into space limitations.

## Forest Service Data General

There are five files included in the dumpfile FOFEM.DMP that can be retrieved from the following DG address:

**Host**: S22L01A
**Staff Area**: FE
**Drawer**: RIS
**Folder**: RIS
**File**: FOFEM.DMP

The files in the dumpfile are ASCII files with the following names and bytesize:

FOFEM.SPP.DAT—Contains tree species information by regions (2898)
FOFEM.COVER.DAT—Contains cover types and their attributes (6432)
FOFEM.FUEL.DAT—Contains fire effects fuel models (23449)
FOFEM.HELP.TXT—Contains help text (45840)
FOFEM.PR—Executable program (673792)—NOT ASCII

The entire dumpfile is about 1,000 blocks. To obtain this dumpfile, you or your system manager must use the file retrieval options in the IS side of your Data General. To load the dumpfile once it is on your system, you can first put the dumpfile in the area (Drawer, Folder) where the loaded FOFEM will permanently reside, then simply type > LOAD/V FOFEM.DMP at the IS command prompt. Once loaded, you can then delete the FOFEM.DMP file from that area with the > DEL FOFEM.DMP command. To execute the program, type the command > X FOFEM at the CLI command line.

## Using FOFEM Through the Fire Effects Information Center

FOFEM is also available, along with the Fire Effects Information System (FEIS), through the Fire Effects Information Center, currently on a Forest Service Computer in Ogden, UT. You do not need to load FOFEM on your computer to run it through the Information Center.

For Forest Service Data General users, access the Information Center using these DG menu choices:

> Utilities
> User Applications
> Info_Center
> FEIS

Other users may access the Information Center through a modem, at no cost other than telephone time. The protocol is 8 Bits, 1 Stop Bit, No Parity. The Information Center has auto baud up to 9600 baud for asynchronous communications using Xon/Xoff flow control. For D400 emulation by SOFTERM, SMARTERM or CEO Connect, use Username:FIRESYS Password:FIRESYS. For VT100 emulation by PROCOMM or CROSSTALK, use Username:FIRESYSVT Password:FIRESYS.

For information about computer access to the Fire Effects Information Center by modem or DG, call the computer specialists at:
(406) 329-4810; (406) 329-4806; or (801) 625-5687.

# Running FOFEM

## Function Keys

There are several function keys that are important for successful program execution. They are defined below using the format where the first term (F1) stands for the function key on your keyboard, and the second term (EXECUTE) is a descriptive term for the purpose of the key, followed by the definition of that key.

**F1 (EXECUTE)**: Commits everything shown on the screen as input into the program, and continues to next menu. Especially useful if the screen contains many acceptable input parameters and user does not wish to <new-line> through all fields.

**SHIFT F1 (HELP)**: Presents information needed to complete the current menu.

**SHIFT-CONTROL F1 (QUICKOUT)**: Stops program execution from anywhere in the program.

**SHIFT F2 (INDEX)**: Presents a list of available input values for current prompt.

**SHIFT-CONTROL F2 (MAIN MENU)**: Returns program execution back to the first or Main screen. Allows user to start over.

**PAGE DOWN for PC, F4 for DG (SCROLL UP)**: Output from FOFEM is presented in moveable windows. Use PAGE DOWN or F4 to scroll down through the output.

**PAGE UP for PC, F3 for DG (SCROLL UP)**: Scroll up through long output screens.

**ESCAPE for PC, F11 for DG (CANCEL/EXIT)**: Presents the previous menu or exits the program if at Main Menu.

**UP ARROW for PC, SHIFT F11 for DG (BACKFIELD)**: Moves cursor back to the previous field.

Once the program is executed, the user can cycle forward and backward through the program using the above keys.

## Menus

The menus in FOFEM were designed to be largely self-explanatory. The user can move between fields using the <enter> or <new-line> key to move forward, and the backfield key (UP ARROW on the PC or SHIFT F11 on the DG) to move backward. As the user moves to a new field, a highlighted definition of the field appears at the bottom of the screen. Often, a default value will already be in the field. To replace this value simply type over it; to accept it use the <new-line> key to move to the next field. If the value of the field is limited to one of a list of possible values, for example, tree species codes, the Index key (SHIFT F2) can be used to select the value from a list.

FOFEM does some error checking and prevents input of wildly inappropriate values. For example, tree height is limited to between 0 and 250 feet, and tree diameter to between 0 and 100 inches. However, inappropriate combinations, such as a 5-foot tall, 25-inch diameter tree, are not screened out.

Moving between menus is done with the EXECUTE key (F1) to move forward, and the CANCEL/EXIT key (ESCAPE on a PC or F11 on DG) to move backward.

Each menu has a help screen that is accessed with the HELP key (SHIFT F1). All the terms used in the menus are defined in appendix A of this guide.

### Output

Program results can be viewed on the terminal. They can also be saved to a file. The file can be printed after exiting FOFEM. If saving to a file, each run should be given a unique file name to prevent overwriting previous output (FOFEM1.OUT or FOFEM2.OUT).

## FOFEM Mailing List and Updates

A FOFEM mailing list is maintained by the Intermountain Fire Sciences Lab in Missoula, MT. Anyone requesting a copy of FOFEM is added to the mailing list and will be notified of updates. It is anticipated that FOFEM will be periodically updated to incorporate new research results. These updates may occur approximately biennially.

## Organization of This Guide

The remainder of this user's guide is in four sections. First the four preliminary FOFEM menus are described. The next three sections cover the fire effects modeled: tree mortality, fuel consumption, and smoke. For each of these fire effects, we first discuss the scope and assumptions of the model. Then the inputs and menus that are common to both the fire effects calculator and the prescribed fire planner are described. Next, the fire effects calculator is discussed, including both inputs and output, followed by the prescribed fire planner, again including inputs and output. Finally, examples are presented. All variables are defined in appendix A. The algorithms used in the model are documented in appendix B. The decision key for selecting algorithms is presented in appendix C. Appendix D lists tree species included in FOFEM, and appendix E lists cover types. Appendix F presents the fuel models used to provide default fuel loadings.

## Preliminary Menus

### Main Menu

The FOFEM main menu is shown in figure 2.

**Choose 1. Fire Effects Calculator** if you wish to predict the effects of a prescribed fire or wildfire.

**Choose 2. Prescribed Fire Planner** if you wish to enter desired fire effects (such as a level of fuel consumption or tree mortality) and have the program determine prescribed fire conditions that should enable you to achieve these effects.

SHIFT CONTROL F2 will return you to this menu from anywhere in the program.

### Geographic Regions

Prediction methods in FOFEM are organized by geographic regions. Figure 1 is a map of the four regions. Figure 3 shows the menu from which you select a geographic region.

**Choose 1. Interior West** for Washington and Oregon east of the Cascade Divide, northeastern and southern California, Idaho, Montana, North and South Dakota, Wyoming, Nebraska, Colorado, Utah, Nevada, Arizona, New Mexico, and West Texas and West Oklahoma.

```
FOFEM                                                     6/26/95  10:28 A
                  ** FOFEM MAIN MENU  Version 4.0 **

       Program FOFEM predicts first order fire effects after a prescribed
       fire or wildfire.  FOFEM was developed by the Fire Effects Research
       Unit, USFS Intermountain Research Station for the purpose of assembling
       state-of-the-art quantitative fire effects relationships in a format
       users can apply to practical problems. If you have any questions about
       FOFEM, contact Bob Keane or Elizabeth Reinhardt for assistance at
       IFSL, Missoula, MT. Be sure to use the HELP key (Shift-F1) if you need
       assistance with the program. Do you wish to use the program to calculate
       effects of fire on a resource, or to plan how to burn an area to
       achieve a desired effect?  Please select option:


                           -->1. Fire Effects Calculator

                              2. Prescribed Fire Planner



       ph: 406-329-4800, FAX: 406-329-4877, DG:S22L01A


ENTER CHOICE:  1




     To exit from FOFEM press Esc


For assistance here (or on any other menu or question), press the HELP key
```

**Figure 2**—FOFEM main menu.

**Choose 2. Pacific West** for western Washington, Oregon, and California; and coastal Alaska.

**Choose 3. North East** for New England and Great Lakes States. Boreal forest types in interior Alaska are also accessed through the North East Region.

**Choose 4. South East** for East Texas and East Oklahoma, and States east of Texas and south of the Great Lakes and New England.

## Cover Type Menu

Figure 4 shows the cover type menu.

Enter the code that corresponds to the cover type of your site. Corresponding SAF (Eyre 1980) cover types or FRES (Forest and Range Ecosystem) types (Garrison and others 1977) are shown in parenthesis.

```
FOFEM                                                      6/26/95  11:05 A
                         FOFEM FIRE EFFECT REGIONS


      First order fire effects algorithms are stratified by regions within
      the United States.  There are currently four regions that are recog-
      nized in FOFEM.  These areas are described in detail in the users
      manual and help screen.  Please decide on the appropriate region and
      enter the corresponding menu option number:


                          -->1. Interior West

                             2. Pacific West

                             3. North East

                             4. South East


ENTER CHOICE:  1
```

**Figure 3**—Geographic regions menu.

The cover type list is too long to fit on a single screen. Use function keys PAGE DOWN (F4 on DG) and PAGE UP (F3 on DG) to scroll through the cover type list.

Cover types not on this list either have not yet been implemented in FOFEM or do not occur in the geographic region you selected.

Select the cover type that best represents the dominant overstory species or species mix currently on the site. The cover type you choose will be used by FOFEM to select appropriate prediction equations and to provide you with default fuel inputs. Selection of a cover type does not limit the tree species available for mortality prediction. All tree species present in the geographic region chosen earlier will be available for mortality predictions.

## Fire Effects Menu

The fire effects menu is shown in figure 5. Select the fire effect that you wish to model. If you are interested in fuel consumption AND smoke, select 3, Smoke, as this option includes both outputs. Options 4 and 5, Soil heating and Potential for Successional Change, are not available in this version.

```
FOFEM                                                          6/26/95  11:06 A
                              COVER TYPE SELECTION


    Many algorithms and default parameters in FOFEM are also stratified by
    vegetation cover type.  Specification of a cover type will customize
    selection of default input values for the user. Please select cover type:


    VEGETATION COVER TYPES AVAILABLE IN FOFEM FOR YOUR SPECIFIED REGION

    112) Black Spruce (SAF 12,204)
    116) White Spruce (SAF 107,201)
    192) Paper Birch (SAF 18)
    194) Paper Birch (SAF 252)
    201) Douglas-fir (SAF 210) Interior
    211) Ponderosa Pine (SAF 237) Interior
    212) Jeffrey Pine (SAF 247)
    221) Western White Pine (SAF 215)
    231) White Fir (SAF 211)
    236) Englemann Spruce Subalpine Fir (SAF 206)
    237) Blue Spruce (SAF 216)
    247) Mountain Hemlock-Subalpine Fir (SAF 205)

    Enter menu number (cover type code) for desired cover type in above
    list. Use PAGE UP and PAGE DOWN to view entire cover type list.
    Enter Cover Type Code:  112
```

**Figure 4**—Cover type menu.

## Tree Mortality

The tree mortality predictions in FOFEM are currently limited to western coniferous tree species and aspen greater than 1 inch d.b.h. Data used to develop the predictions were taken primarily from prescribed fires, but the predictions should also apply reasonably well to wildfires. Some postfire insect interactions are implicitly included in these predictions, as trees damaged by insects after burning were not excluded from the data. Major postfire insect attacks are not modeled, however. Root damage is not explicitly modeled, although it may be correlated with cambial damage in many cases.

For the fire effects calculator, FOFEM requires an estimate of either flame length or scorch height as input to tree mortality predictions. In the prescribed fire planner, a range of flame lengths or scorch heights is the output. In either case, the fire behavior itself is not modeled in FOFEM. A fire behavior program such as BEHAVE (Andrews and Chase 1989) or RxWindow (Andrews and Bradshaw 1990) can be used to estimate flame length or scorch height, if this further analysis is desired.

```
FOFEM                                                  6/26/95  11:20 A
                              FIRE EFFECTS MENU

     Program FOFEM allows the user to calculate the First Order Fire
     Effects for the following attributes.  The user can select a resource
     effect option by entering a number corresponding to the desired attri-
     bute.  You can only evaluate fire effects on ONE resource at this time.
     You must rerun FOFEM to evaluate another effect.  Please enter the
     desired menu option:

                         --> 1. Tree Mortality

                             2. Fuel Consumption

                             3. Smoke

                             4. Soil Heating

                             5. Potential for Successional Change

ENTER CHOICE:  1
```

**Figure 5**—Fire effects menu.

## Assumptions

A species-specific method of predicting tree mortality is not currently available for many tree species. To provide predictive capability for these species, we have followed the assumption of Ryan and Reinhardt (1988) that differences in fire-caused tree mortality in trees of differing species and sizes can be accounted for primarily by differences in bark thickness and proportion of tree crown killed (fig. 6). This allows us to use mortality equations across species as long as we can estimate bark thickness, tree height, crown ratio, and scorch height.

Either scorch height or flame length may be used as the driving variable for tree mortality computations. If flame length is selected, scorch height is computed using Van Wagner's (1973) scorch height model and assumes a temperature of 77 °F and a midflame windspeed of 0 mph (fig. 7). These values seem conservative for many situations since computed scorch height varies little with temperature between 40 and 80 °F, and windspeeds between 0 and 10 mph. These ranges encompass many prescribed fire conditions. At higher windspeeds typical of many wildfires, computed scorch heights actually decrease at a given flame length, so predicted scorch height, and consequently, tree mortality will be overpredicted. Entering scorch height directly allows the user to bypass these assumptions, if they are of concern. Van Wagner's scorch height model was developed using data from stands of

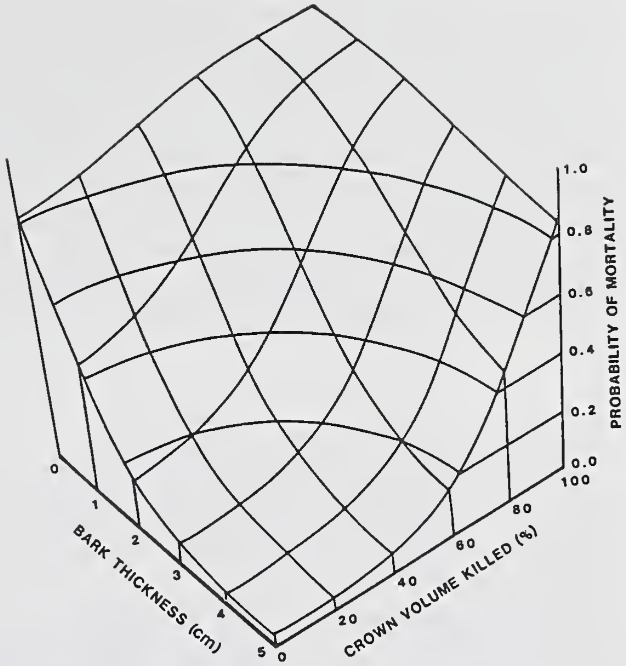


**Figure 6**—A conceptual model of tree mortality.

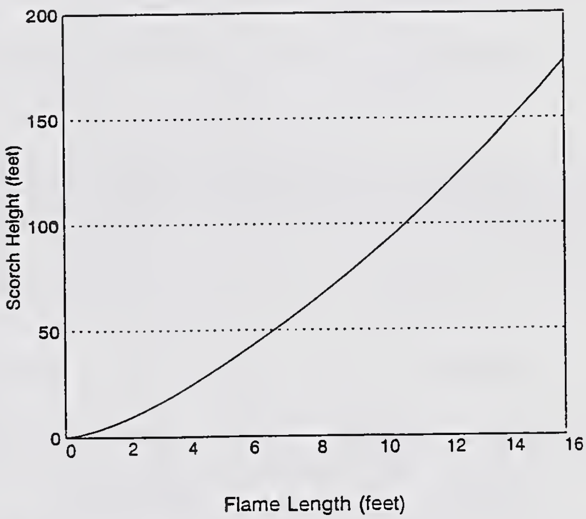


**Figure 7**—Van Wagner's crown scorch model, shown for midflame windspeed of 0 mph and ambient temperature of 77 °F.

red pine on flat ground; it can be expected to perform poorly on steep slopes, at ridgetops, and in stands with large openings in the canopy. Again, using scorch height as a predictive variable, instead of flame length, allows the user to avoid the sources of error in predicting scorch height. This may be an especially good option when predicting effects of fire after the fact—in such a case scorch height can be observed in the field.

In predicting stand mortality, FOFEM assumes a continuous fire. If a burn is very discontinuous or patchy, and the user can estimate the proportion of the area burned, then the per acre estimates of tree mortality computed by FOFEM can be adjusted by multiplying them by the proportion burned.

## General Inputs

General inputs are shown in figure 8.

Tree mortality computations can be applied to an individual tree or to all trees in a stand. Individual tree calculations allow a more detailed tree description; stand calculations provide an easy way to assess the effect of fire on an entire stand.

Fire severity is only used for predicting aspen mortality. In low severity fires, aspen mortality is less than in moderate or higher severity fires. For all other species, predicted mortality does not depend on this variable. Low severity fires are those that char but do not completely consume litter, and may leave unburned patches. Moderate severity fires consume litter and some duff. Severe fires generally consume all litter and duff.

```
FOFEM                                                        6/26/95   11:13 A
                       GENERAL TREE MORTALITY INPUT DATA


     This screen asks for general information that is used in the computation
     of tree mortality. The values are either used directly in mortality equa-
     tions, or used to key to the right mortality algorithm. Please complete
     the following fields:


     Tree Mortality Computation (T-Tree, S-Stand):  T

     Fire severity (E-extreme, V-very high, H-high, M-moderate, L-low):  H

     Fire Intensity Measure to use (F-Flame Length, S-Scorch Height): F








         EXECUTE: Y
```

**Figure 8**—General tree mortality inputs.

```
FOFEM                                                    6/26/95  11:13 A

                        INDIVIDUAL TREE MORTALITY


                 Species code:              Tree DBH (in):


                Tree Height (ft):          Live crown ratio:


                                                 EXECUTE: Y
```

**Figure 9**—Individual tree input.

Fire Intensity Measure allows the user to choose between flame length and scorch height (see previous section). If you are predicting mortality from a fire that has already occurred, you can reduce variability in predictions by entering scorch height rather than flame length. If you choose to enter flame length, FOFEM computes expected scorch height using Van Wagner's crown scorch model to predict tree mortality.

Individual tree calculations require as input: species, diameter, height, crown ratio, and either flame length or scorch height (fig. 9). Enter values to describe the tree of interest.

**Species code**: Enter a six letter species code, such as PINPON for ponderosa pine. Use function key SHIFT F2 (INDEX) to see a list of available tree species.

**Tree D.B.H.**: Enter tree diameter at breast height (4.5 feet) in inches. FOFEM will compute bark thickness from species and diameter using equations listed in table 1.

**Table 1**—Bark thickness equations used in FOFEM. BTH = bark thickness, inches; D.B.H. = tree diameter at breast height, inches. From Keane and others (1989); Keane and others (1996).

| Equation no. | Species | Equation |
|---|---|---|
| 1 | Ponderosa pine | BTH = –.0376 + .0584 D.B.H. |
| 2 | Douglas-fir | BTH = .065 D.B.H. |
| 3 | Western larch | BTH = –.045 + .0629 D.B.H. |
| 4 | Grand fir | BTH = .043 D.B.H. |
| 5 | Western redcedar | BTH = .152 + .021 D.B.H. |
| 6 | Western hemlock | BTH = .022 + .043 D.B.H. |
| 7 | Subalpine fir | BTH = .015 D.B.H. |
| 8 | Lodgepole pine | BTH = .027 + .0143 D.B.H. |
| 9 | Whitebark pine | BTH = .027 + .022 D.B.H |
| 10 | Engelmann spruce | BTH = .126 + .025 D.B.H. |
| 11 | Quaking aspen | BTH = .052 + .033 D.B.H. |
| 12 | Western white pine | BTH = .054 + .025 D.B.H. |

**Table 2**—Tree height equations used in FOFEM. HT = tree height, feet; D.B.H. = tree diameter at breast height, inches.

| Equation no. | Species | Equation |
|---|---|---|
| 1 | Ponderosa pine | $HT = -38.43 + 37.08\ D.B.H.^{.417}$ |
| 2 | Douglas-fir | $HT = -38.43 + 37.08\ D.B.H.^{.417}$ |
| 3 | Western larch | $HT = -43.69 + 42.38\ D.B.H.^{.439}$ |
| 4 | Grand fir | $HT = -30.94 + 29.57\ D.B.H.^{.546}$ |
| 5 | Western redcedar | $HT = -26.23 + 26.10\ D.B.H.^{.522}$ |
| 6 | Western hemlock | $HT = -43.69 + 42.38\ D.B.H.^{.439}$ |
| 7 | Subalpine fir | $HT = -38.43 + 37.08\ D.B.H.^{.417}$ |
| 8 | Lodgepole pine | $HT = 327.76 - 333.52\ D.B.H.^{-.112}$ |
| 9 | White bark pine | $HT = 327.76 - 333.52\ D.B.H.^{-.112}$ |
| 10 | Engelmann spruce | $HT = -26.23 + 26.10\ D.B.H.^{.522}$ |
| 11 | Quaking aspen | $HT = 327.76 - 333.52\ D.B.H.^{.112}$ |
| 12 | Western white pine | $HT = -30.94 + 29.57\ D.B.H.^{.546}$ |

**Tree height**: Enter tree height in feet, or leave blank if you wish FOFEM to estimate tree height from the species and diameter. FOFEM will use diameter-height relationships in table 2.

**Live crown ratio**: Enter the ratio of live crown to total tree height, using whole number codes (for example, 4 to indicate that live crown length is 40 percent of tree height). If left blank, FOFEM will assume a value based on tree species (appendix D).

For stand data entry, you may enter any number of species-diameter-density combinations (fig. 10) by repeatedly entering the three fields:

**Species code**: enter a six letter species code (PINPON for ponderosa pine) or use function key SHIFT F2 (INDEX) to choose species from a list. If a tree species is not on this list, either it does not occur in the geographical region you selected, or there are no mortality equations currently available for that species.

**Tree D.B.H.**: enter tree diameter at breast height in inches.

**Number of trees**: enter number of trees per acre of this species-diameter combination, or use 100 to get output in terms of percent mortality.

To terminate stand data entry, use the CANCEL/EXIT key (F11 on DG or ESCAPE on PC). (You may have to wait a couple of seconds) FOFEM will

```
FOFEM                                                        6/26/95   11:14 A

                           TREE STAND DATA ENTRY


     Now enter tree density (t/ac) by species and 1 inch diameter class.

     Press the ESCAPE key to end tree entry for stand in question and wait

     for program to execute--this may take awhile.


         Species code:          Tree DBH (in):   0   Number of trees:     0
```

**Figure 10**—Stand input.

compute bark thickness, tree height, and crown ratio for each stand component you enter. If you wish to override these computations, use the individual tree option rather than the stand option.

## Fire Effects Calculator

For the individual tree computations, flame length or scorch height is a required input. Both are measured in feet. Output for the individual tree calculations is the predicted probability of mortality for the tree, based on its characteristics and the flame length or scorch height (fig. 11). In figure 11, for example, a 12 inch ponderosa pine with flame length of 4 feet has a

```
FOFEM                                                      6/26/95  11:15 A

TREE MORTALITY -- INPUT VALUES AND RESULTS FROM FIRE EFFECTS CALCULATOR

Individual tree mortality

Title: Results of FOFEM model execution on date:  6/26/95

Zone: Interior West                    Cover Type: Douglas-fir (SAF 210) Interi


Species: PINPON                          Diameter (DBH in inches): 12.0

Tree height (ft):  66.                   Live crown ratio: 4

Scorch height (ft):  23.8                Flame Length (ft):   4.0



Probability of Mortality:   .25

Mortality Algorithm:     1



PROBABILITY OF MORTALITY BY DIFFERENT FIRE INTENSITY LEVELS FOR ENTERED TREE

Spp                               Flame Lengths (feet)

Code        1    2    3    4    5    6    7    8    9   10   11   12   13   14

-------------------------------------------------------------------------------

PINPON    .25  .25  .25  .25  .25  .30  .89  .99  .99  .99  .99  .99  .99  .99

-------------------------------------------------------------------------------



END OF TREE MORTALITY PREDICTIONS.  PRESS PAGE UP TO REVIEW DISPLAYED OUTPUT..


                                          Do you wish to print results? Y
```

**Figure 11**—Individual tree mortality output.

TITLE: Results of FOFEM model execution on date: 6/26/95

*** FIRE EFFECTS CALCULATOR ***

TREE MORTALITY MODULE: Stand tree mortality
REGION: Interior West
COVER TYPE: Douglas-fir (SAF 210) Interior

FLAME LENGTH (FT): 4.0

ORIGINAL STAND DENSITY AS INPUT TO FOFEM

| Species Code | Diameter classes (in) 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| PINPON | 0 | 0 | 150 | 0 | 0 | 100 | 0 | 0 | 0 | 0 |
| PSEMEN | 0 | 0 | 150 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| TOTALS | 0 | 0 | 300 | 0 | 0 | 100 | 0 | 0 | 0 | 0 |

DBH classes (in): 2: 0-2, 4: 3-4, 6: 5-6, 8: 7-8, 10: 9-10and so on...

POSTFIRE STAND DENSITY (TREES/ACRE)

| Species Code | Diameter classes (in) 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| PINPON | 0 | 0 | 66 | 0 | 0 | 75 | 0 | 0 | 0 | 0 |
| PSEMEN | 0 | 0 | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| TOTALS | 0 | 0 | 80 | 0 | 0 | 75 | 0 | 0 | 0 | 0 |

DBH classes (in): 2: 0-2, 4: 3-4, 6: 5-6, 8: 7-8, 10: 9-10and so on...

STAND DENSITY (TREES/ACRE) OF TREES KILLED BY THE FIRE

| Species Code | Diameter classes (in) 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| PINPON | 0 | 0 | 84 | 0 | 0 | 25 | 0 | 0 | 0 | 0 |
| PSEMEN | 0 | 0 | 136 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| TOTALS | 0 | 0 | 220 | 0 | 0 | 25 | 0 | 0 | 0 | 0 |

DBH classes (in): 2: 0-2, 4: 3-4, 6: 5-6, 8: 7-8, 10: 9-10and so on...

**Figure 12**—Stand prediction output.

probability of mortality of 0.25. This can be interpreted to mean that a quarter of such trees will likely die.

A table showing the probability of mortality over a range of flame lengths or scorch heights is also included. In figure 11, notice that at flame lengths of 5 feet and less, mortality is unchanging. These flames are not causing any crown scorch at all (scorch height is less than crown base height), so mortality is determined solely from bark thickness. A thinner barked tree with the same crown base height would have a greater, but also constant, mortality level for these flame lengths. At 6-foot flame lengths, mortality begins to increase, indicating that some amount of crown scorch is occurring. At flame lengths of 8 feet and over, probability of mortality is near 1, indicating near total crown scorch. Thinner barked trees will reach predicted mortality of near 1 before their crowns are completely scorched.

For the stand computations, stand-average flame length or crown scorch height is a required input. Output for the stand calculations includes several tables (fig. 12). Three stand tables show original stand density as input by the user, postfire stand density as computed by FOFEM, and the trees killed by the fire, by species and diameter class. Probability of mortality is listed for each species/diameter combination entered. Then probabilities of mortality over a range of flame lengths are shown for each species/diameter combination,

PROBABILITY OF MORTALITY FOR EACH SPECIES/DIAMETER ENTRY

| Species Code | Diameter (inch) | Number Trees | Prob Mort | Mort Equ Number |
|---|---|---|---|---|
| PINPON | 6 | 150 | .56 | 1 |
| PINPON | 12 | 100 | .25 | 1 |
| PSEMEN | 6 | 150 | .91 | 1 |

AVERAGE MORTALITY PROBS FOR 2 FT FLAMES BY SPECIES/DIAMETER ENTRY

| Spp Code | Tree DBH | Flame Lengths (feet) 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| PINPON | 6 | .6 | .6 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| PINPON | 12 | .2 | .2 | .3 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| PSEMEN | 6 | .5 | .9 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| AVERAGES | 8 | .4 | .6 | .8 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

Stand Tree Mortality

TREE MORTALITY INDEXES:
Average probability of mortality: .61
Number of trees killed by the fire: 245
Average tree diameter (DBH) killed by fire (inch): 6.6
Average probability of mortality for trees 4+ in DBH: .61
Total prefire number of trees: 400

**Figure 12**—(Con.)

allowing users to assess the sensitivity of the predictions to flame length. Finally, summary statistics are presented for the stand: average probability of mortality, total number of trees per acre killed, average diameter of trees killed, and average probability of mortality for trees larger than 4 inches d.b.h.

## Prescribed Fire Planner

In the prescribed fire planner, as in the fire effects calculator, there is an individual tree option as well as a stand option. You must enter the upper and lower limits of acceptable probability of mortality for the tree (fig. 13). Defaults of 0 and 50 percent can be typed over to change values. FOFEM will compute the flame lengths or scorch heights that are associated with these mortality levels. Remember that very narrow ranges of acceptable mortality will result in narrow ranges of acceptable fire intensity, and a more difficult prescription.

Output is the flame length or scorch height that corresponds to those probabilities (fig. 14). A flame length or scorch height of 0.1 is printed whenever the mortality algorithm cannot be solved for a particular mortality level. It should be interpreted to mean that any fire will result in at least that level of mortality.

In figure 14, for example, the user has requested the range of flame lengths that corresponds to 0 to 30 percent mortality for 15 inch western hemlock. FOFEM output shows that any fire will result in greater than 0 percent mortality, while flame lengths of 4.6 feet are associated with 30 percent mortality.

A second portion of the table shows the relationship between fire intensity (flame length or scorch height), and a range of probabilities. This information may be useful in evaluating additional alternatives.

In the stand option, ranges of acceptable mortality must be entered for every species/diameter combination. The output (fig. 15) is similar to that of the individual tree option except additional table rows exist for each stand component. You can enter a different minimum and maximum acceptable percent mortality for each stand component. You might wish, for example, to have high mortality of an encroaching understory, and low mortality for a

```
                                                    6/26/95    1:05 P

                         TREE MORTALITY LEVEL TARGETS


           Enter MINimum acceptable level mortality:   0

           Enter MAXimum acceptable level mortality:  30


                                  EXECUTE Y
```

**Figure 13**—Menu for entering desired tree mortality range.

```
TITLE: Results of FOFEM model execution on date: 7/13/95

                        *** PRESCRIBED FIRE PLANNER ***

 Tree Mortality Module: Individual tree mortality


 REGION: Interior West
 COVER TYPE: Black Spruce (SAF 12,204)

 INDIVIDUAL TREE INPUT VALUES:

   Species: Tsuga heterophylla -- Western Hemlock
   Diameter (DBH in inches):  15.0
   Tree height (ft):  95.4
   Live crown ratio: 8

 MINimum probability of mortality:   .00    Target Flame Length  (ft):       .1

 MAXimum probability of mortality: 30.00    Target Flame Length  (ft):      4.6

 Mortality Equation Number:     1


 FLAME LENGTHS (FT) NEEDED TO ACHIEVE MORTALITY LEVELS FOR THE ENTERED TREE

 Species                       Probability of Mortality
 Code        0.10   0.20   0.30   0.40   0.50   0.60   0.70   0.80   0.90   1.00

 TSUHET        .1     .1    4.6    5.2    5.7    6.1    6.5    6.9    7.6   10.4


 Note: Fire intensity of 0.1 indicates that ANY fire will exceed mortality
level.

 Flame lengths never produce scorch heights that are greater than
 the height of the tree.
```

**Figure 14**—Output for planning option—individual tree mortality.

desired overstory. The wider the ranges you select, the more likely that there will be a fire intensity range that meets all your stand mortality goals. If there is no overlap in the recommended fire intensity ranges for different stand components, mortality goals are unlikely to be achieved by prescribed fire.

## Example 1: Salvage Sale

Suppose that you are planning a salvage sale for a stand of Douglas-fir and ponderosa pine that was recently underburned in a wildfire. A wide range of tree sizes is present; the largest trees have diameters of around 20 inches. Scorch heights average 30 feet. You wish to use FOFEM to help prepare marking guidelines for a salvage sale.

Figure 16 shows sample FOFEM output generated to help with this task. The Fire Effects Calculator was used in this example. When entering stand data, we used 100 in every case for number of trees so that we could view expected mortality in terms of percent. The output indicates that if you wish

```
TITLE: Results of FOFEM model execution on date: 6/26/95

                         *** PRESCRIBED FIRE PLANNER ***

 TREE MORTALITY MODULE: Stand tree mortality

 REGION: Interior West
 COVER TYPE: Douglas-fir (SAF 210) Interior

 Tree     Tree     Trees     Min      Target    Max      Target
 Species  Dia      per       Accept   Flame     Accept   Flame
 Code     DBH      acre      Mort     Length    Mort     Length
 Name     (inch)   (t/ac)    Prob     (feet)    Prob     (feet)
 ---------------------------------------------------------------
 PINPON      12      100       10.0        .1      50.0      6.4
 PSEMEN       6      300       50.0       2.8     100.0      5.7

                         *** FIRE PLANNING SIMULATOR ***

 FLAME LENGTHS (FT) NEEDED TO ACHIEVE MORTALITY LEVELS FOR ENTERED TREES

 Species  Tree                  Probability of Mortality
 Code     DBH      0.10  0.20  0.30  0.40  0.50  0.60  0.70  0.80  0.90  1.00

 PINPON   12         .1    .1   6.0   6.2   6.4   6.5   6.7   6.8   7.1   8.1
 PSEMEN    6         .1    .1    .1    .1   2.8   3.2   3.4   3.7   4.0   5.7
 ----------------------------------------------------------------------------

 Note: fire intensity of 0.1 indicates that ANY fire will exceed mortality
level.

 Flame lengths never produce scorch heights that are greater than
 the height of the tree.
```

**Figure 15**—Output for planning option—stand mortality.

to remove all the trees that are likely (probability >50 percent) to die, pine less than 8 inches in diameter, and fir less than 12 inches in diameter should be removed. A different selection criteria might be obtained if you wish to retain only the trees that are very likely to live (probability less than 25 percent of dying). In that case you would remove pine less than 12 inches and fir less than 14 inches in diameter.

## Example 2: Prescribed Fire

Suppose that you are planning a prescribed fire to reduce Douglas-fir encroachment into an old growth ponderosa pine stand. The overstory pine averages 20 inches in diameter; the Douglas-fir are mostly less than 8 inches in diameter. You are willing to accept no more than 10 percent mortality in the overstory, but hope to remove at least 60 percent of the understory.

Figure 17 shows FOFEM output that can help you develop your prescription. In this case the Prescribed Fire Planner was chosen. The output shows

TITLE: Results of FOFEM model execution on date: 6/26/95

*** FIRE EFFECTS CALCULATOR ***

TREE MORTALITY MODULE: Stand tree mortality
REGION: Interior West
COVER TYPE: Douglas-fir (SAF 210) Interior

SCORCH HEIGHT (FT): 30.0

ORIGINAL STAND DENSITY AS INPUT TO FOFEM

| Species | Diameter classes (in) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Code | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 |
| PINPON | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| PSEMEN | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| TOTALS | 0 | 0 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 |

DBH classes (in): 2: 0-2, 4: 3-4, 6: 5-6, 8: 7-8, 10: 9-10and so on...

POSTFIRE STAND DENSITY (TREES/ACRE)

| Species | Diameter classes (in) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Code | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 |
| PINPON | 0 | 0 | 9 | 57 | 67 | 75 | 81 | 86 | 89 | 91 |
| PSEMEN | 0 | 0 | 2 | 14 | 41 | 66 | 80 | 87 | 91 | 93 |
| TOTALS | 0 | 0 | 11 | 71 | 108 | 141 | 161 | 173 | 180 | 184 |

DBH classes (in): 2: 0-2, 4: 3-4, 6: 5-6, 8: 7-8, 10: 9-10and so on...

STAND DENSITY (TREES/ACRE) OF TREES KILLED BY THE FIRE

| Species | Diameter classes (in) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Code | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 |
| PINPON | 0 | 0 | 91 | 43 | 33 | 25 | 19 | 14 | 11 | 9 |
| PSEMEN | 0 | 0 | 98 | 86 | 59 | 34 | 20 | 13 | 9 | 7 |
| TOTALS | 0 | 0 | 189 | 129 | 92 | 59 | 39 | 27 | 20 | 16 |

DBH classes (in): 2: 0-2, 4: 3-4, 6: 5-6, 8: 7-8, 10: 9-10and so on...

**Figure 16**—Example 1: salvage sale.

```
TITLE: Results of FOFEM model execution on date: 6/26/95

                        *** PRESCRIBED FIRE PLANNER ***

TREE MORTALITY MODULE: Stand tree mortality


REGION: Interior West
COVER TYPE: Douglas-fir (SAF 210) Interior

Tree     Tree       Trees      Min        Target     Max        Target
Species  Dia        per        Accept     Flame      Accept     Flame
Code     DBH        acre       Mort       Length     Mort       Length
Name     (inch)     (t/ac)     Prob       (feet)     Prob       (feet)
-----------------------------------------------------------------------------
PINPON      20        100          .0         .1       10.0        7.4
PSEMEN       8        100        60.0        4.0      100.0        6.7
-----------------------------------------------------------------------------


FLAME LENGTHS (FT) NEEDED TO ACHIEVE MORTALITY LEVELS FOR ENTERED TREES

Species   Tree                  Probability of Mortality
Code      DBH      0.10  0.20  0.30  0.40  0.50  0.60  0.70  0.80  0.90  1.00
-----------------------------------------------------------------------------
PINPON    20        7.4   7.9   8.1   8.3   8.4   8.6   8.7   8.9   9.3  10.1
PSEMEN     8         .1    .1    .1   3.4   3.7   4.0   4.2   4.5   4.9   6.7
---------------------------------------------------------------------

Note: fire intensity of 0.1 indicates that ANY fire will exceed mortality
level.

Flame lengths never produce scorch heights that are greater than
the height of the tree.
```

**Figure 17**—Example 2: prescribed fire.

that for 10 percent mortality of the overstory pine, flame lengths can be up to 7.4 feet long. For the smaller fir, flame lengths need to be at least 4 feet to achieve 60 percent mortality. A prescribed flame length of 4 to 7 feet should meet both mortality objectives.

Notice that the target flame length corresponding to a minimum acceptable mortality of 0 for the pine is 0.1 foot. A flame length of 0.1 is printed whenever the mortality algorithm cannot be solved for a particular mortality level. It should be interpreted to mean that any fire will result in at least that level of mortality. This can be seen again in the next table. For the 8-inch Douglas-fir, the table indicates that any fire will result in at least 30 percent mortality.

## Fuel Consumption

FOFEM predicts the quantity of fuel consumed by prescribed fire or wildfire. Fuels may be natural fuels or activity fuels. Fuels may be piled. Mineral soil exposed by fire is also predicted as a part of the fuel consumption module, since it occurs as a result of forest floor (duff and litter) consumption.

FOFEM uses the following fuel classes: duff; litter; 0-1 inch, 1-3 inch, and 3 inch+ diameter dead woody fuels; herbaceous, shrub, and conifer regeneration; live conifer foliage; and fine live conifer branchwood. Conifer regeneration refers to seedlings affected by surface fire. The conifer foliage and branchwood categories represent fuels on larger trees affected only by crown fire. Shrub and grassland types typically lack woody fuels, conifer fuels, and often duff.

## Assumptions

One major assumption made in FOFEM for predicting or planning for fuel consumption is that the entire area of concern experienced fire. FOFEM does not predict fire effects accurately for patchy or nonuniform burns. For discontinuous burns, results should be weighted by the percent of the area burned.

## General Inputs

A number of general fuel inputs are required by the fuel consumption module. Figure 18 shows the FOFEM menu for these inputs. Select choices that best describe your fuel situation. The choices you make in this menu

```
FOFEM                                                          6/26/95   1:17 P
                           GENERAL FUEL INPUT DATA

     This screen asks for general information to customize the default values
     presented to the user for modification. These values are also used to key
     the equations used to calculate fire effects.  Please complete following
     fields:

     Fuel Category (N-natural, P-piles, S-slash): N

     Dead Fuel Adjustment Factor (T-typical,L-light, H-heavy): T

     Moisture Conditions (V-very dry, D-dry, M-moderate, W-wet): D

     Fire intensity (E-extreme, V-very high, H-high, M-moderate, L-low): H

     Will this fire burn tree crowns? (N-no, Y-yes): N

     Tree crown biomass loading (T-typical, S-sparse, A-abundant): T

     Herbaceous Density (T-typical, S-sparse, A-abundant): T

     Shrub Density (T-typical, S-sparse, A-abundant): T

     Tree Regeneration Density (T-typical, S-sparse, A-abundant): T

     Season of Burn (S-spring, M-summer, F-fall, W-winter): F


     EXECUTE: Y
```

**Figure 18**—General fuel consumption input.

determine both the prediction equations FOFEM will select, and the default inputs provided for you. You will have an opportunity in the next screen to further customize the fuel description. This menu always contains the same fields, but not all are used in every fuel modeling situation. For example, if you are burning grasslands, the fields describing woody fuel and tree crowns are irrelevant and will not affect calculations.

**Fuel category**: FOFEM will provide fuel consumption predictions for natural fuels, for piles, or for slash.

**Dead fuel adjustment factor**: Your selection here determines the default loadings of duff, litter, and woody fuel that FOFEM provides. Typical values and adjustment factors are shown in appendix F.

**Moisture conditions for duff and wood 3+**: The value you select will determine default moisture contents of duff and large woody fuel. It will also key to flaming/smoldering ratios used to determine emissions (as discussed later in the Smoke section.)

**Expected fire intensity**: This value is used only for slash fuels in the Pacific West and Interior West. Intense fires are thought to go out more quickly, resulting in less consumption of large fuel for a given moisture content (Ottmar and others 1993). Appendix A gives guidelines for determining expected fire intensity based on the size of the burn unit, ignition time, and fuel moisture.

**Will this fire burn tree crowns**: If you wish, you can model consumption of canopy fuels, including foliage and fine branchwood. This consumption would occur in a crown fire, and is modeled primarily to compare emissions from a crown fire to those from an underburn. This question refers to canopy fuels on live standing trees, not to activity fuels.

**Tree crown biomass loading**: If you answered yes to the previous question, you can select typical, sparse, or abundant crown biomass. The value will be used in determining the default foliage and fine branchwood canopy loadings that FOFEM provides.

The next three fields, Herbaceous Density, Shrub Density, and Tree Regeneration Density, allow FOFEM to select default loadings of these three fuel components. See appendix F for listings of the loadings used by FOFEM for sparse, typical, and abundant fuel situations. For forest types, these fuels are a relatively minor component of the fuel complex. For shrub and grassland ecosystems, these fuels may comprise the entire fuel complex. In either case, use your judgment to enter a value that represents the relative density for the cover type selected. Sparse shrubs in a shrub type may contribute more fuel than abundant shrubs in a forest type.

**Season of burn**: Season is used as a predictive variable for consumption of sagebrush, grass, and large woody fuels. FOFEM assumes fall burns occur after substantial curing of live fuels has taken place, and spring burns occur before greenup in grasslands.

For several southern pine types (longleaf, loblolly, slash), an additional menu is displayed. Fuel loadings depend in part on the age of rough, and whether the stand is a natural stand or a plantation (fig. 19). Please provide this information.

To predict fuel consumption, preburn fuel loadings are needed. Preburn fuel loadings may be estimated ocularly, but using photo series guides is more accurate (Fischer 1981), and sampling with line inventory is the most accurate method (Brown 1974). For some applications, none of these methods is practical. To provide realistic default inputs for fuel loadings, we have

```
FOFEM                                                    6/26/95   1:18 P
                        SOUTHEAST PINE INFORMATION


     You must now enter additional information on SouthEastern Pine
     cover types to calculate fuel consumption and smoke.


     Enter managed condition of site in question:

           (P-plantation, N-natural): N

          Enter age of rough (years):    5


     EXECUTE: Y
```

**Figure 19**—Pop-up menu for southern pine.

developed a set of fuel models for FOFEM. Fuel models are described in appendix F. Fuel models are provided for natural and slash fuels. Fuel models are keyed to forest cover type. There is not a unique model for every cover type; rather, there are a number of models, most developed for a particular cover type. Cover types lacking in fuels data were assigned a fuel model from a cover type thought to have similar fuels (table 5, appendix F).

Figure 20 shows the menu provided for entering preburn loadings. The menu appears with default values in each field, derived from the fuel models. To replace any value, simply type in the replacement. All values are in tons/acre, except duff depth and diameter of 3+ woody fuel, which are in inches. If you alter the duff depth, duff loading will be recalculated by FOFEM.

To accept all the default values and continue to the next menu, use function key F1 (EXECUTE).

## Fire Effects Calculator

Moisture contents of duff and large woody fuel are required inputs (fig. 21). Duff Code and Wood 3+ Code refer to the method used for estimating moisture content of duff and large woody fuel. For duff, code E refers to measured duff moisture of the entire duff layer, L is the measured moisture content of the lower duff layer, N is the National Fire Danger Rating System 1,000-hour fuel moisture index (NFDR TH), and A is the Adjusted NFDR TH index (Ottmar and Sandberg 1983b). For large woody fuel, code M refers to measured fuel moisture, while N and A have the same meanings as for duff moisture. The most accurate predictions of fuel consumption are obtained by using measured moisture contents. Lower duff moisture usually gives a more accurate prediction of duff consumption than entire duff moisture, however, for some cover types and for shallow duff layers, no prediction equations using lower duff moisture are available. If this is the case, FOFEM will not accept the choice L for duff code and an error message will be shown on the bottom of the screen. In some situations, measured fuel moistures may not

```
FOFEM                                                    6/26/95   1:19 P
                              FUEL INPUT VALUES

     Presented below are the customized fuel input defaults for FOFEM selected
     from the information entered on previous screens. Modify these values to
     best describe your site.  First are loadings in tons per acre by fuel
     component. Secondary various data needed by FOFEM to calculate fire
     effects:

                                Fuel Loadings (t/ac)

     Litter:     .6            Wood 0-1 in dia:     .9   Wood 1-3 in dia:     .8

     Wood 3+ in dia:   7.0     Duff:  10.0               Herb:   .20

     Shrub:   .20              Regen:   .10              Crown foliage:   6.0

     Crown small branchwood:   3.0


                            Important Fuel Parameters

     Duff depth (in):   1.0         Mean Diameter 3+ Woody Fuel:   5.0


     EXECUTE: Y
```

**Figure 20**—Fuel loadings.

be available. National Fire Danger Rating System 1,000-hour fuel moisture code (NFDR TH) or the adjusted code (ANFDR TH) can be used as a substitute for measured duff and large woody fuel moisture.

For the Pacific Northwest Region, number of days since significant rainfall is a required input for predicting duff consumption (Ottmar and others 1993) (fig. 22). Enter the number of days since a rain event that saturated the duff layer (0.5 inches of rain).

FOFEM summarizes the input information and then summarizes fuel values (prefire load, consumption, postfire load, and percent consumption) by fuel component (fig. 23). The right-hand column in the table gives an equation number that can be looked up in appendix B for a description of the prediction equation used.

For forest types only, a second output table is provided. Use function key F4 (SCROLL DOWN) to view it. This table shows duff depth reduction, percent duff consumption, mineral soil exposure, and diameter reduction of the 3+ inch woody material. Duff depth reduction and percent duff

```
FOFEM                                                 6/26/95   1:19 P

                          FUEL MOISTURES

           You now can alter fuel moisture values for duff

            and Wood (3+ inch).  Enter code and moisture:

              Duff Code: E          Duff Moisture (%):  75

            Wood 3+ Code: M       Wood 3+ Moisture (%):  15

                                               EXECUTE: Y
```

**Figure 21**—Fuel moisture.

```
                                                      6/26/95   1:19 P
                    DAYS SINCE SIGNIFICANT RAIN

                  Enter days since 0.50 in rain:  20
```

**Figure 22**—Pop-up menu for days since rain, PNW region.

consumption are estimated from separate equations and will not usually give the same results. The estimates of percent duff consumption are usually more robust, but you may be interested in duff depth consumption if, for example, residual duff depth is important to you.

## Prescribed Fire Planner

For the prescribed fire planner, you must enter the desired minimum and maximum percent consumption for each fuel component (fig. 24). FOFEM will compute a range of NFDR TH hour moistures that corresponds to desired consumption levels for duff, mineral soil exposure, and 3+ inch woody fuel. For the other fuel components, FOFEM will simply determine whether or not the desired consumption limits are feasible (see "yes" in fig. 25). This is because consumption of these fuels is often not highly correlated with their moisture contents.

TITLE: Results of FOFEM model execution on date: 7/17/95

*** FIRE EFFECTS CALCULATOR ***
FUEL CONSUMPTION CALCULATIONS

REGION: Interior West
COVER TYPE: Larch (SAF 212)
FUEL TYPE: Natural
FUEL ADJ FACTOR: Typical
DUFF MOISTURE (%): 75.0 - Entire
WOOD (3+ IN) MOISTURE (%): 15.0 - Actual

FUEL CONSUMPTION TABLE

| Fuel Component Name | Preburn Load (t/acre) | Consumed Load (t/acre) | Postburn Load (t/acre) | Percent Reduced (%) | Equation Reference Number |
|---|---|---|---|---|---|
| Litter | .6 | .6 | .0 | 100.0 | 39 |
| Wood (0-1 inch) | .9 | .8 | .1 | 90.0 | 21 |
| Wood (1-3 inch) | .8 | .5 | .3 | 65.0 | 25 |
| Wood (3+ inch) | 7.0 | 5.8 | 1.2 | 82.2 | 31 |
| Duff | 10.0 | 5.2 | 4.8 | 51.7 | 2 |
| Herbaceous | .2 | .2 | .0 | 100.0 | 22 |
| Shrubs | .2 | .1 | .1 | 60.0 | 23 |
| Tree regeneration | .2 | .1 | .1 | 60.0 | 24 |
| Crown branchwood | 3.0 | .0 | 3.0 | .0 | 38 |
| Crown foliage | 6.0 | .0 | 6.0 | .0 | 37 |
| Total Fuels | 28.9 | 13.3 | 15.6 | 46.0 | |

FIRE EFFECTS ON FOREST FLOOR COMPONENTS

| Forest Floor Component | Preburn Condition | Amount Consumed | Postburn Condition | Percent Reduced | Equation Number |
|---|---|---|---|---|---|
| Duff Depth (in) | 1.0 | .6 | .4 | 60.0 | 6 |
| Duff Depth (%) | 1.0 | .5 | .5 | 51.7 | 2 |
| Min Soil Exp (%) | .0 | 31.0 | 31.0 | 31.0 | 10 |
| Log Diameter (in) | 5.8 | 3.3 | 2.4 | 57.8 | 31 |

**Figure 23**—Fuel consumption output.

The prescribed fire planner is available for forest types only.

If you plan to use this program to set prescription parameters, remember that if you set very narrow consumption targets you will get very small prescription windows. If you are concerned only with one fuel component (for example woody fuel), set your targets for other components to be 0 for minimum and 100 for maximum, so that only the fuel component of interest will restrict your prescription.

FOFEM provides a summary output table showing, for each fuel component, the prefire load, minimum acceptable consumption specified by the user, corresponding moisture content, maximum acceptable consumption, corresponding moisture content, and equation number used for the calculation (fig. 25). For example, in figure 25, the user is interested in restricting consumption of large woody fuel to between 20 and 70 percent. FOFEM

FOFEM 6/26/95 1:20 P

FUEL CONSUMPTION TARGETS

You must now specify a range of acceptable values for fuel consumption. These values are entered as a percent of preburn quantity. The user must specify both the min and max values as a percent of fuel component loading. Enter targets:

| Fuel Component | Min % Consumption | Max % Consumption |
|---|---|---|
| Litter Loading ................ | 20 | 100 |
| 0-1 in Dia Woody Loading ....... | 50 | 100 |
| 1-3 in Dia Woody Loading ....... | 30 | 90 |
| 3+ in Dia Woody Loading ........ | 20 | 60 |
| Duff Loading .................. | 20 | 100 |
| Duff Depth .................... | 20 | 100 |
| Mineral Soil Exposed .......... | 20 | 50 |

EXECUTE: Y

**Figure 24**—Fuel consumption targets.

TITLE: Results of FOFEM model execution on date: 8/ 1/95

*** PRESCRIBED FIRE PLANNER ***
FUEL CONSUMPTION CALCULATIONS

REGION: Interior West
COVER TYPE: Ponderosa Pine (SAF 237) Interior
FUEL TYPE: Slash - Sound
FUEL ADJ FACTOR: Typical

| Fuel Component | Preburn Load t/ac | Min Acc Consume | NFDR-TH Moist-% | Max Acc Consume | NFDR-TH Moist-% | Equation Number |
|---|---|---|---|---|---|---|
| Litter | 3.9 | .0 | YES | 100.0 | YES | 39 |
| Wood (0-1 inch) | 5.0 | .0 | YES | 100.0 | YES | 21 |
| Wood (1-3 inch) | 8.0 | .0 | YES | 100.0 | YES | 261 |
| Wood (3+ inch) | 12.0 | 20.0 | 30.1 | 70.0 | 15.2 | 34 |
| Duff | 5.0 | .0 | 27.3 | 100.0 | 3.5 | 3 |
| Duff Depth (in) | .6 | .0 | 19.1 | 100.0 | 13.4 | 7 |
| Min Soil Exp (%) | 0.0 | .0 | 26.3 | 100.0 | .0 | 11 |

**Figure 25**—Fuel consumption planning output.

computes an NFDR TH moisture of 30 to correspond to 20 percent consumption, and 15 to correspond to 70 percent consumption. Values of NFDR TH between 15 and 30 are likely to result in acceptable results; values outside this range can be expected to result in unacceptable consumption.

## Example 3: Spring Burn

Suppose you are planning a spring burn for wildlife habitat enhancement. The primary objective of the burn is to stimulate shrub production, but you also want to estimate fuel consumption to see if total site impacts are acceptable. The stand is Sierra Nevada mixed conifer with heavy natural fuels. Since no fuel inventory has been done, you plan to use default values provided by FOFEM.

Figure 26 shows the FOFEM output generated for this situation. The first column of values shows the default preburn fuel loads provided by FOFEM

```
TITLE: Results of FOFEM model execution on date: 6/27/95

                        *** FIRE EFFECTS CALCULATOR ***
                         FUEL CONSUMPTION CALCULATIONS

 REGION: Pacific West
 COVER TYPE: Sierra Nevada Mixed Conifer (SAF 243)
 FUEL TYPE: Natural
 FUEL ADJ FACTOR: Heavier than Normal
 DUFF MOISTURE (%):  120.0 - Entire
 WOOD (3+ IN) MOISTURE (%):   25.0 - Actual
```

FUEL CONSUMPTION TABLE

| Fuel Component Name | Preburn Load (t/acre) | Consumed Load (t/acre) | Postburn Load (t/acre) | Percent Reduced (%) | Equation Reference Number |
|---|---|---|---|---|---|
| Litter | 1.8 | 1.8 | .0 | 100.0 | 39 |
| Wood (0-1 inch) | 1.3 | 1.2 | .1 | 90.0 | 21 |
| Wood (1-3 inch) | 1.9 | 1.2 | .7 | 65.0 | 25 |
| Wood (3+ inch) | 32.0 | 14.7 | 17.3 | 46.0 | 31 |
| Duff | 56.0 | 24.7 | 31.3 | 44.2 | 8 |
| Herbaceous | .3 | .3 | .0 | 100.0 | 22 |
| Shrubs | .5 | .3 | .2 | 60.0 | 23 |
| Tree regeneration | .3 | .2 | .1 | 60.0 | 24 |
| Crown branchwood | 3.0 | .0 | 3.0 | .0 | 38 |
| Crown foliage | 6.0 | .0 | 6.0 | .0 | 37 |
| Total Fuels | 103.1 | 44.4 | 58.7 | 43.1 | |

FIRE EFFECTS ON FOREST FLOOR COMPONENTS

| Forest Floor Component | Preburn Condition | Amount Consumed | Postburn Condition | Percent Reduced | Equation Number |
|---|---|---|---|---|---|
| Duff Depth (in) | 3.0 | 1.3 | 1.7 | 44.2 | 8 |
| Duff Depth (%) | 3.0 | 1.3 | 1.7 | 44.2 | 8 |
| Min Soil Exp (%) | .0 | 30.7 | 30.7 | 30.7 | 14 |
| Log Diameter (in) | 5.8 | 1.5 | 4.2 | 26.5 | 31 |

**Figure 26**—FOFEM output generated for example 3: spring burn.

based on cover type (Sierra Nevada mixed conifer), fuel type (natural), and dead fuel adjustment factor (heavy). Notice that more than half of the preburn fuel loading is duff. The next columns show predicted consumption, postburn fuel load, and percent consumption. The final column shows the equation number that was used to derive these predictions. These equations are listed in appendix B. In this example, around half of the duff and large woody fuel are expected to burn. The second part of the table shows that around 30 percent mineral soil exposure can be expected.

## Example 4: Broadcast Burning

Suppose you are developing a prescription for broadcast burning logging slash in a western white pine stand. The duff is 2 inches deep; small woody fuels are estimated at 10 tons/acre and large woody fuels at 25 tons/acre. You wish to achieve 10 to 50 percent mineral soil exposure, at least 50 percent consumption of small woody fuels, and no more than 50 percent consumption of large woody fuels.

Figure 27 shows the fuel consumption targets. Note that for litter and duff the targets are set to be 0 and 100 percent, since their consumption is not

```
FOFEM                                                          6/27/95  10:35 A

                          FUEL CONSUMPTION TARGETS


You must now specify a range of acceptable values for fuel consumption.  These
values are entered as a percent of preburn quantity.  The user must specify both
the min and max values as a percent of fuel component loading.  Enter targets:


Fuel Component                   Min % Consumption     Max % Consumption

-------------------------------------------------------------------------

Litter Loading ................         0                   100
0-1 in Dia Woody Loading .......        50                   100
1-3 in Dia Woody Loading .......        50                   100
3+ in Dia Woody Loading ........        0                    50
Duff Loading ...................        0                   100
Duff Depth .....................        0                   100
Mineral Soil Exposed ...........        10                   50

-------------------------------- ----------------     ----------------





EXECUTE: Y
```

**Figure 27**—Fuel consumption targets for example 4: broadcast burning.

```
TITLE: Results of FOFEM model execution on date: 6/27/95

                    *** PRESCRIBED FIRE PLANNER ***
                     FUEL CONSUMPTION CALCULATIONS

 REGION: Interior West
 COVER TYPE: Western White Pine (SAF 215)
 FUEL TYPE: Slash - Sound
 FUEL ADJ FACTOR: Typical
```

| Fuel Component | Preburn Load t/ac | Min Acc Consume | NFDR-TH Moist-% | Max Acc Consume | NFDR-TH Moist-% | Equation Number |
|---|---|---|---|---|---|---|
| Litter | 2.8 | .0 | YES | 100.0 | YES | 39 |
| Wood (0-1 inch) | 3.0 | 50.0 | YES | 100.0 | YES | 21 |
| Wood (1-3 inch) | 7.0 | 50.0 | YES | 100.0 | YES | 261 |
| Wood (3+ inch) | 25.0 | .0 | 34.6 | 50.0 | 22.1 | 34 |
| Duff | 30.0 | .0 | 27.3 | 100.0 | 3.5 | 3 |
| Duff Depth (in) | 2.0 | .0 | 24.5 | 100.0 | 5.4 | 7 |
| Min Soil Exp (%) | 16.1 | 10.0 | 23.5 | 50.0 | 12.2 | 11 |

**Figure 28**—FOFEM output for example 4: broadcast burning.

specified in the objectives. Figure 28 shows the output of this run. For the litter and small woody fuels, FOFEM simply prints a "YES," indicating that the 50 percent plus consumption objective is likely to be achieved. For the large woody fuels, two NFDR TH values are printed, corresponding to the upper and lower consumption limits. For 0 consumption, NFDR TH needs to be 35 percent; for 50 percent consumption, it should be 22 percent. Values between 22 and 35 should be acceptable for the large woody fuel consumption objective. For mineral soil exposure, NFDR TH values between 12 and 23 are recommended. The recommended ranges for mineral soil exposure and for large woody fuel consumption barely overlap. This indicates that these prescription objectives will be difficult to achieve, and should possibly be reconsidered.

## Smoke

FOFEM models emission production, not visibility or dispersion. Categories of emissions estimated are PM2.5 (particulate matter less than 2.5 microns in diameter), PM10 (particulate matter less than 10 microns in diameter), and CO (carbon monoxide). As an option to aid managers in dispersion modeling, future versions of FOFEM will create a file that can be used as input to the dispersion model PUFF. There is great overlap between the fuel consumption and smoke modules of FOFEM.

### Assumptions

The assumptions and methods used in FOFEM for modeling emissions were taken from Hardy and others (1996). Emissions production depends both on fuel consumption and on the combustion efficiency of the fire.

**Table 3**—Combustion efficiencies and flaming-smoldering fractions for fuel components burned under different moisture conditions (adapted from Hardy and others 1994).

| Fuel component | Combustion efficiency[a] | | Wet | | Normal | | Dry | |
|---|---|---|---|---|---|---|---|---|
| | *Flaming* | *Smoldering* | *F*[b] | *S*[c] | *F* | *S* | *F* | *S* |
| Litter, wood 0-1 inch | 0.95 | — | 1.0 | 0.0 | 1.0 | 0.0 | 1.0 | 0.0 |
| Wood 1-3 inches | 0.92 | — | 1.0 | 0.0 | 1.0 | 0.0 | 1.0 | 0.0 |
| Wood 3+ inches | 0.92 | 0.76 | 0.5 | 0.5 | 0.7 | 0.3 | 0.8 | 0.2 |
| Herb, shrub, regen | 0.85 | — | 1.0 | 0.0 | 1.0 | 0.0 | 1.0 | 0.0 |
| Duff | 0.90 | 0.76 | 0.5 | 0.5 | 0.4 | 0.6 | 0.4 | 0.6 |
| Canopy fuels | 0.85 | — | 1.0 | 0.0 | 1.0 | 0.0 | 1.0 | 0.0 |

[a]Combustion efficiency is the portion of the carbon released from fuel consumption that is in the form of $CO_2$.
[b]Fraction of total consumption that occurs in flaming combustion.
[c]Fraction of total consumption that occurs in smoldering combustion.

Total consumption of each fuel component is modeled as in the fuel consumption module. Consumption of each fuel component is allocated into proportions consumed in flaming and smoldering combustion (table 3). These proportions depend on whether the burn is a wet, moderate, or dry burn, as specified by the user. Litter, live fuels, and small branchwood are assumed to burn entirely in flaming combustion. An increasing proportion of large woody fuel burns in flaming combustion in drier conditions, while an increasing proportion of duff burns in smoldering combustion in drier conditions.

Each fuel component also has a combustion efficiency assigned for flaming and smoldering consumption. Combustion efficiency is the proportion of the carbon released from burning that is in the form of $CO_2$ (carbon dioxide). A value of 1.0 would indicate perfect combustion: a fire that produced nothing but $CO_2$ and water—no particulate matter or CO. Lower values indicate smokier burns. Combustion efficiency is greater in flaming combustion than in smoldering. Emission factors are computed from combustion efficiency, following procedures in Ward and others (1993). Emission factors and the equations for computing them are listed in table 4.

## General Inputs

Inputs are identical to those used for fuel consumption.

**Table 4**—Emission factors for PM10, PM2.5, and CO, lbs/ton of fuel consumed, by fuel component, for wet, moderate, and dry burns. Emission factors were computed from values in table 3 and equations in Ward and others (1994).

| | PM10[a] | | | PM2.5[b] | | | CO[c] | | |
|---|---|---|---|---|---|---|---|---|---|
| **Fuel component** | **Wet** | **Moderate** | **Dry** | **Wet** | **Moderate** | **Dry** | **Wet** | **Moderate** | **Dry** |
| Litter, wood 0-1 inch | 9.3 | 9.3 | 9.3 | 7.9 | 7.9 | 7.9 | 52.4 | 52.4 | 52.4 |
| Wood 1-3 inches | 14.0 | 14.0 | 14.0 | 11.9 | 11.9 | 11.9 | 111.4 | 111.4 | 111.4 |
| Wood 3+ inches | 26.6 | 21.6 | 19.1 | 22.5 | 18.3 | 16.2 | 268.9 | 205.8 | 174.4 |
| Herb, shrub, regen | 25.1 | 25.1 | 25.1 | 21.3 | 21.3 | 21.3 | 249.2 | 249.2 | 249.2 |
| Duff | 28.2 | 30.4 | 30.4 | 23.9 | 25.8 | 25.8 | 288.6 | 316.1 | 316.1 |
| Canopy fuels | 25.1 | 25.1 | 25.1 | 21.3 | 21.3 | 21.3 | 249.2 | 249.2 | 249.2 |

[a]Emission factor for PM10 is computed as 1.18 * emission factor for PM2.5.
[b]Emission factor for PM2.5 is computed as 2 * (67.4 – 66.8 * Combustion efficiency).
[c]Emission factor for CO is computed as 2 * (961 – 984 * Combustion efficiency).

TITLE: Results of FOFEM model execution on date: 6/26/95

*** FIRE EFFECTS CALCULATOR ***
SMOKE SUMMARY TABLE - FUEL CONSUMPTION CALCULATIONS

REGION: South East
COVER TYPE: Lobolly Pine Coastal (SAF 81)
FUEL TYPE: Natural
FUEL ADJ FACTOR: Typical
DUFF MOISTURE (%): 75.0 - Entire
WOOD (3+ IN) MOISTURE (%): 15.0 - Actual

FUEL CONSUMPTION TABLE

| Fuel Component Name | Preburn Load (t/acre) | Consumed Load (t/acre) | Postburn Load (t/acre) | Percent Reduced (%) | Equation Reference Number |
|---|---|---|---|---|---|
| Litter | 1.0 | 1.0 | .0 | 100.0 | 40 |
| Wood (0-1 inch) | .0 | .0 | .0 | .0 | 213 |
| Wood (1-3 inch) | .0 | .0 | .0 | .0 | 262 |
| Wood (3+ inch) | .0 | .0 | .0 | .0 | 31 |
| Duff | 4.4 | 4.4 | .0 | 100.0 | 16 |
| Herbaceous | .0 | .0 | .0 | .0 | 22 |
| Shrubs | 2.2 | 1.3 | .9 | 59.7 | 234 |
| Tree regeneration | .1 | .1 | .0 | 100.0 | 241 |
| Crown branchwood | .0 | .0 | .0 | .0 | 38 |
| Crown foliage | .0 | .0 | .0 | .0 | 37 |
| Total Fuels | 7.7 | 6.8 | .9 | 88.7 | |

SMOKE SUMMARY TABLE - SMOKE EMISSIONS CALCULATIONS

| Forest Floor Component | Ave Combust Efficiency | PM10 Emission (lbs/acre) | PM2.5 Emission (lbs/acre) | CO Emission (lbs/acre) |
|---|---|---|---|---|
| Litter | .95 | 9.3 | 7.9 | 52.4 |
| Wood (0-1 inch) | .00 | .0 | .0 | .0 |
| Wood (1-3 inch) | .00 | .0 | .0 | .0 |
| Wood (3+ inch) | .00 | .0 | .0 | .0 |
| Duff | .82 | 133.8 | 113.5 | 1390.8 |
| Herbaceous | .00 | .0 | .0 | .0 |
| Shrubs | .85 | 32.2 | 27.4 | 320.0 |
| Tree regeneration | .85 | 2.5 | 2.1 | 24.9 |
| Crown branchwood | .00 | .0 | .0 | .0 |
| Crown foliage | .00 | .0 | .0 | .0 |
| Total Fuels | .84 | 177.8 | 150.9 | 1788.2 |

**Figure 29**—Smoke prediction outputs.

## Fire Effects Calculator

Inputs are the same as in fuel consumption.

FOFEM provides an output table showing, for each fuel component, fuel consumption, given the preburn load, and documents the equation used to derive the consumption estimates. The second part of the table indicates average combustion efficiency and emissions of PM2.5, PM10, and CO (fig. 29). Average combustion efficiency for a fuel component is a weighted average of flaming combustion efficiency and smoldering combustion efficiency, weighted by the proportion of total consumption of that fuel component that occurs in flaming and smoldering combustion. The average combustion efficiency of the total fuel bed (.84 in fig. 29 for example) is a weighted average of the combustion efficiencies for each fuel component, this time weighted by total consumption of each component. This value indicates the efficiency of the burn as a whole, considering all fuel components and flaming/smoldering ratios for each. Values typically range from .75 to .95.

The third part of the output table shows, for each fuel component, prefire loading, flaming, smoldering and total consumption, and the percentage of total PM2.5 emissions that come from that fuel component.

## Prescribed Fire Planner

For the prescribed fire planner, you must enter the minimum and maximum values for acceptable emissions (lbs per acre) (fig. 30). Usually only maximum values are of interest, so minimums can be left at 0. FOFEM will compute the total fuel consumption and the associated NFDR TH hour fuel moisture that correspond to the minimum and maximum emission targets, and recommend a range of NFDR TH moisture conditions under which a fire may occur without exceeding user-specified emissions levels.

SMOKE SUMMARY -- FLAMING AND SMOLDERING SUMMARY

| Fuel Component Name | Prefire loading ton/acre | Moist Content (%) | ------- Flaming (t/ac) | Consumption Smoldering (t/ac) | ------- Total (t/ac) | PM25 Emissions (%) |
|---|---|---|---|---|---|---|
| Litter | 1.0 | -- | 1.0 | .0 | 1.0 | 5.2 |
| Wood (0-1 inch) | .0 | -- | .0 | .0 | .0 | .0 |
| Wood (1-3 inch) | .0 | -- | .0 | .0 | .0 | .0 |
| Wood (3+ inch) | .0 | 15.0 | .0 | .0 | .0 | .0 |
| Duff | 4.4 | 75.0 | 1.8 | 2.6 | 4.4 | 75.2 |
| Herbaceous | .0 | -- | .0 | .0 | .0 | .0 |
| Shrubs | 2.2 | -- | 1.3 | .0 | 1.3 | 18.1 |
| Tree regeneration | .1 | -- | .1 | .0 | .1 | 1.4 |
| Crown branchwood | .0 | -- | .0 | .0 | .0 | .0 |
| Crown foliage | .0 | -- | .0 | .0 | .0 | .0 |
| Total Fuels | 7.7 | -- | 4.1 | 2.6 | 6.8 | 100.0 |

**Figure 29**—(Con.)

```
                                                   6/26/95    1:21 P
                         SMOKE EMISSION TARGETS


          Enter acceptable limits - PM 2.5 Particulate(lb/ac)

                  Minimum:      0         Maximum:    200

          Enter acceptable limits - PM 10 Particulate (lb/ac)

                  Minimum:      0         Maximum:    200

          Enter acceptable limits - Carbon Monoxide   (lb/ac)

                  Minimum:      0         Maximum:   1000


                              EXECUTE: Y
```

**Figure 30**—Smoke targets.

FOFEM first computes expected consumption and emissions of litter, small woody and live fuels. Then, if the target is not exceeded by these fuels, FOFEM determines how much consumption of duff and large woody fuels is acceptable, and the NFDR TH hour moisture that should achieve this level (fig. 31).

### Example 5: Smoke Production

Predict the smoke production for the prescribed burn described in example 3. Compare this smoke production to that expected from a very dry summer wildfire when crown foliage is consumed.

Figures 32 and 33 show the FOFEM output generated for this example. Total fuel consumption is 44 tons/acre for the prescribed burn compared to 78 for the wildfire. The difference is due to additional duff and large woody fuel consumption, and consumption of canopy fuels in the wildfire. Total PM10 production is 1,125 lbs/acre for the prescribed fire compared to 1,933 lbs/acre for the wildfire. This kind of comparison may be useful for comparing alternatives in environmental assessments.

## Soil Heating

Soil heating from prescribed fire or wildfire can result in changes to soil structure and water-absorbing capacity, soil nutrients, and microbial populations, and can cause root mortality. Excessive soil heating adversely affects soil productivity and stability (Hungerford and others 1991).

TITLE: Results of FOFEM model execution on date: 6/26/95

*** PRESCRIBED FIRE PLANNER ***
SMOKE SUMMARY TABLE

REGION: Interior West
COVER TYPE: Larch-Douglas-fir (SAF 212)
FUEL TYPE: Natural
FUEL ADJ FACTOR: Typical

Fuels where consumption is modeled independently of NFDR-TH hr moist content

| Fuel Component | Preburn Load t/ac | Consumed Load t/ac | Postburn Load t/ac | Percent Reduced | Equation Number |
|---|---|---|---|---|---|
| Litter | .6 | .6 | .0 | 100.0 | 39 |
| Wood (0-1 inch) | .9 | .8 | .1 | 90.0 | 21 |
| Wood (1-3 inch) | .8 | .5 | .3 | 65.0 | 25 |
| Herbaceous | .2 | .2 | .0 | 100.0 | 22 |
| Shrubs | .2 | .1 | .1 | 60.0 | 23 |
| Tree regeneration | .1 | .1 | .0 | 60.0 | 24 |
| Crown branchwood | 3.0 | .0 | 3.0 | .0 | 33 |
| Crown foliage | 6.0 | .0 | 6.0 | .0 | 37 |
| Total Fuels | 11.8 | 2.3 | 9.5 | 19.6 | |

EMISSION SUMMARY OF FUELS NOT DEPENDENT ON DUFF OR WOOD (3+ IN) MOISTURE

PM 2.5 Emissions (lb/ac): 45.0
PM 10 Emissions (lb/ac): 53.1
Carbon Monoxide Emissions (lb/ac): 515.1

Fuels using NFDR-TH hr moisture to predict consumption and smoke emissions

| Smoke Part Size Class | Target Level (max or min) | Emissions Target lbs per acre | Total Consume Target (t/ac) | NFDR-TH hr Moist % Required | Preburn Wood 3+ +Duff (t/ac) | Wood 3+ Fuel Consumed (t/ac) | Duff Load Consumed (t/ac) |
|---|---|---|---|---|---|---|---|
| PM 2.5 | Min Acc | .0 | .0 | NO | 17.0 | .0 | .0 |
| PM 2.5 | Max Acc | 200.0 | 10.3 | 20.3 | 17.0 | 5.0 | 2.9 |
| PM 10 | Min Acc | .0 | .0 | NO | 17.0 | .0 | .0 |
| PM 10 | Max Acc | 200.0 | 8.7 | 22.0 | 17.0 | 4.2 | 2.2 |
| CO | Min Acc | .0 | .0 | NO | 17.0 | .0 | .0 |
| CO | Max Acc | 1000.0 | 4.5 | 25.9 | 17.0 | 1.7 | .6 |

NOTE: YES indicates emission targets will be met regardless of NFDR-TH moisture
NO indicates emission targets are exceeded by other fuels (lit,twig,etc).

**Figure 31**—Smoke planning output.

*** FIRE EFFECTS CALCULATOR ***
SMOKE SUMMARY TABLE - FUEL CONSUMPTION CALCULATIONS
REGION: Pacific West
COVER TYPE: Sierra Nevada Mixed Conifer (SAF 243)
FUEL TYPE: Natural
FUEL ADJ FACTOR: Heavier than Normal
DUFF MOISTURE (%): 120.0 - Entire
WOOD (3+ IN) MOISTURE (%): 25.0 - Actual

FUEL CONSUMPTION TABLE

| Fuel Component Name | Preburn Load (t/acre) | Consumed Load (t/acre) | Postburn Load (t/acre) | Percent Reduced (%) | Equation Reference Number |
|---|---|---|---|---|---|
| Litter | 1.8 | 1.8 | .0 | 100.0 | 39 |
| Wood (0-1 inch) | 1.3 | 1.2 | .1 | 90.0 | 21 |
| Wood (1-3 inch) | 1.9 | 1.2 | .7 | 65.0 | 25 |
| Wood (3+ inch) | 32.0 | 14.7 | 17.3 | 46.0 | 31 |
| Duff | 56.0 | 24.7 | 31.3 | 44.2 | 8 |
| Herbaceous | .2 | .2 | .0 | 100.0 | 22 |
| Shrubs | .3 | .2 | .1 | 60.0 | 23 |
| Tree regeneration | .1 | .1 | .0 | 60.0 | 24 |
| Crown branchwood | 3.0 | .0 | 3.0 | .0 | 38 |
| Crown foliage | 6.0 | .0 | 6.0 | .0 | 37 |
| Total Fuels | 102.6 | 44.1 | 58.5 | 43.0 | |

| Forest Floor Component | Ave Combust Efficiency | PM10 Emission (lbs/acre) | PM2.5 Emission (lbs/acre) | CO Emission (lbs/acre) |
|---|---|---|---|---|
| Litter | .95 | 16.7 | 14.2 | 94.3 |
| Wood (0-1 inch) | .95 | 10.9 | 9.2 | 61.3 |
| Wood (1-3 inch) | .92 | 17.3 | 14.7 | 137.6 |
| Wood (3+ inch) | .87 | 317.7 | 269.1 | 3026.8 |
| Duff | .82 | 752.0 | 638.2 | 7819.2 |
| Herbaceous | .85 | 5.0 | 4.3 | 49.8 |
| Shrubs | .85 | 3.8 | 3.2 | 37.4 |
| Tree regeneration | .85 | 1.5 | 1.3 | 15.0 |
| Crown branchwood | .00 | .0 | .0 | .0 |
| Crown foliage | .00 | .0 | .0 | .0 |
| Total Fuels | .85 | 1124.9 | 954.2 | 11241.4 |

| Fuel Component Name | Prefire loading ton/acre | Moist Content (%) | ------- Consumption ------- Flaming (t/ac) | Smoldering (t/ac) | Total (t/ac) | PM25 Emissions (%) |
|---|---|---|---|---|---|---|
| Litter | 1.8 | -- | 1.8 | .0 | 1.8 | 1.5 |
| Wood (0-1 inch) | 1.3 | -- | 1.2 | .0 | 1.2 | 1.0 |
| Wood (1-3 inch) | 1.9 | -- | 1.2 | .0 | 1.2 | 1.5 |
| Wood (3+ inch) | 32.0 | 25.0 | 10.3 | 4.4 | 14.7 | 28.2 |
| Duff | 56.0 | 120.0 | 9.9 | 14.8 | 24.7 | 66.9 |
| Herbaceous | .2 | -- | .2 | .0 | .2 | .4 |
| Shrubs | .3 | -- | .2 | .0 | .2 | .3 |
| Tree regeneration | .1 | -- | .1 | .0 | .1 | .1 |
| Crown branchwood | 3.0 | -- | .0 | .0 | .0 | .0 |
| Crown foliage | 6.0 | -- | .0 | .0 | .0 | .0 |
| Total Fuels | 102.6 | -- | 24.8 | 19.3 | 44.1 | 100.0 |

**Figure 32**—Prescribed burn predictions for example 5.

*** FIRE EFFECTS CALCULATOR ***
SMOKE SUMMARY TABLE - FUEL CONSUMPTION CALCULATIONS

REGION: Pacific West
COVER TYPE: Sierra Nevada Mixed Conifer (SAF 243)
FUEL TYPE: Natural
FUEL ADJ FACTOR: Heavier than Normal
DUFF MOISTURE (%): 40.0 - Entire
WOOD (3+ IN) MOISTURE (%): 10.0 - Actual

FUEL CONSUMPTION TABLE

| Fuel Component Name | Preburn Load (t/acre) | Consumed Load (t/acre) | Postburn Load (t/acre) | Percent Reduced (%) | Equation Reference Number |
|---|---|---|---|---|---|
| Litter | 1.8 | 1.8 | .0 | 100.0 | 39 |
| Wood (0-1 inch) | 1.3 | 1.2 | .1 | 90.0 | 21 |
| Wood (1-3 inch) | 1.9 | 1.2 | .7 | 65.0 | 25 |
| Wood (3+ inch) | 32.0 | 26.9 | 5.1 | 84.1 | 31 |
| Duff | 56.0 | 38.7 | 17.3 | 69.0 | 8 |
| Herbaceous | .2 | .2 | .0 | 100.0 | 22 |
| Shrubs | .3 | .2 | .1 | 60.0 | 23 |
| Tree regeneration | .1 | .1 | .0 | 60.0 | 24 |
| Crown branchwood | 3.0 | 1.5 | 1.5 | 50.0 | 38 |
| Crown foliage | 6.0 | 6.0 | .0 | 100.0 | 37 |
| Total Fuels | 102.6 | 77.7 | 24.9 | 75.8 | |

| Forest Floor Component | Ave Combust Efficiency | PM10 Emission (lbs/acre) | PM2.5 Emission (lbs/acre) | CO Emission (lbs/acre) |
|---|---|---|---|---|
| Litter | .95 | 16.7 | 14.2 | 94.3 |
| Wood (0-1 inch) | .95 | 10.9 | 9.2 | 61.3 |
| Wood (1-3 inch) | .92 | 17.3 | 14.7 | 137.6 |
| Wood (3+ inch) | .89 | 514.0 | 436.0 | 4693.3 |
| Duff | .82 | 1175.2 | 997.4 | 12219.5 |
| Herbaceous | .85 | 5.0 | 4.3 | 49.8 |
| Shrubs | .85 | 3.8 | 3.2 | 37.4 |
| Tree regeneration | .85 | 1.5 | 1.3 | 15.0 |
| Crown branchwood | .85 | 37.7 | 31.9 | 373.8 |
| Crown foliage | .85 | 150.6 | 127.8 | 1495.2 |
| Total Fuels | .85 | 1932.6 | 1640.0 | 19177.2 |

| Fuel Component Name | Prefire loading ton/acre | Moist Content (%) | ------- Consumption ------- Flaming (t/ac) | Smoldering (t/ac) | Total (t/ac) | PM25 Emissions (%) |
|---|---|---|---|---|---|---|
| Litter | 1.8 | -- | 1.8 | .0 | 1.8 | .9 |
| Wood (0-1 inch) | 1.3 | -- | 1.2 | .0 | 1.2 | .6 |
| Wood (1-3 inch) | 1.9 | -- | 1.2 | .0 | 1.2 | .9 |
| Wood (3+ inch) | 32.0 | 10.0 | 21.5 | 5.4 | 26.9 | 26.6 |
| Duff | 56.0 | 40.0 | 15.5 | 23.2 | 38.7 | 60.8 |
| Herbaceous | .2 | -- | .2 | .0 | .2 | .3 |
| Shrubs | .3 | -- | .2 | .0 | .2 | .2 |
| Tree regeneration | .1 | -- | .1 | .0 | .1 | .1 |
| Crown branchwood | 3.0 | -- | 1.5 | .0 | 1.5 | 1.9 |
| Crown foliage | 6.0 | -- | 6.0 | .0 | 6.0 | 7.8 |
| Total Fuels | 102.6 | -- | 73.9 | 47.8 | 77.7 | 100.0 |

**Figure 33**—Summer wildfire predictions for example 5.

A model for predicting soil heating has been developed by Campbell and others (1994, 1995). We expect to incorporate this model into the next major FOFEM revision.

The model predicts a time-temperature profile at specified depths. Depths at which critical temperatures occur can also be predicted. Inputs to the model include soil moisture content, soil parent origin, and the heat flux at the soil surface. It is hoped that this heat flux will be derived from FOFEM fuel consumption algorithms.

## Potential for Successional Change

Methods for predicting potential for successional change have been conceptualized by Peter Stickney and are expected to be added to future releases of FOFEM. FOFEM will not predict plant succession following fire as this is a longer-term, second-order fire effect that depends not only on prefire conditions and fire intensity, but also on postfire events and environment. Instead, we plan to elicit from the user a description of the prefire plant community, and then compute a relative measure of successional potential for a range of fire treatments.

## Conclusions

We plan for FOFEM to be a continually evolving program in response to changes in users' needs and research availability. The existing prediction methods for tree mortality, fuel consumption, and smoke production will be added to, and in some cases replaced, as new research refines our understanding of these fire effects. New modules for predicting soil heating, potential for successional change, and erosion potential are planned. Links to data bases and other models are possible. We welcome your comments and suggestions! Send them to us at:

Intermountain Fire Sciences Lab
P.O. Box 8089
Missoula, MT 59807
or call us at: (406) 329-4800

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## Appendix A—List of Variables with Definitions and Units

**ANFDR TH**: Percent. Adjusted NFDR TH moisture code. This is the adjusted value meant to more accurately reflect moisture of logging slash (Ottmar and Sandberg 1983b).

**CO**: Lbs per acre. Carbon monoxide emission.

**Cover Type Code**: Three-digit numeric code to select forest cover type. Correspondence to SAF forest cover types or Forest and Range Ecosystem types (FRES) is shown.

**Crown Foliage**: Tons per acre. Needles on live standing trees expected to burn only in a crown fire.

**Crown Small Branchwood**: Tons per acre. This includes the 0-$\frac{1}{4}$ inch branchwood on live standing trees expected to burn only in a crown fire.

**Dead Fuel Adjustment Factor**: Fuels are described as typical T, light L, or heavy H. These adjustment factors are used in providing default values for duff, litter, and woody fuel loadings and represent mean, median, and third quartiles of sampled fuels.

**Duff**: Tons per acre. Includes fermentation ($O_1$) and humus ($O_2$) layers. FOFEM will estimate prefire duff loading from duff depth and an assumed bulk density.

**Duff Code**: Method of estimating duff moisture. E entire duff layer, measured moisture; L lower duff, measured moisture; N NFDR TH moisture index; A adjusted NFDR TH index.

**Duff Depth**: Inches. Includes fermentation ($O_1$) and humus ($O_2$) layers.

**Duff & Wood 3+ Moisture Conditions**: For estimating fuel consumption or smoke production, users are asked to describe fuel moisture conditions as Very Dry V, Dry D, Moderate M, or Wet W. This value is used to provide default duff and large woody fuel moistures, and also to set flaming/smoldering ratios.

**Expected Fire Intensity**: Extreme E, Very High V, High H, Medium M, or Low L. The expected fire intensity is used to adjust large woody fuel consumption of slash in the Pacific Northwest (Hall 1991; Ottmar and others 1993). Predicted diameter reduction is reduced if intensity is greater than medium; by 33 percent if extreme, 22 percent if very high, and 11 percent if high. Ottmar and others (1993) offered the following guidelines for estimating intensity:

| | Extreme | Very high | High |
|---|---|---|---|
| Unit size (acres) | >10 | Any size | Any size |
| 10-hour fuel moisture content (percent) | <15 | ≤15 | ≤18 |
| Adjusted 1,000-hour moisture (percent) | ≤40 | ≤50 | ≤50 |
| Ignition time (minutes) | | | |
| For units less than 20 acres | < acres | <2*acres | <4*acres |
| For units more than 20 acres | <0.5*acres | <acres + 20 | <2*acres + 40 |

**Expected Fire Severity**: Extreme E, Very High V, High H, Medium M, or Low L. Used for predicting mortality of aspen. Low severity fires result in lower mortality than other fires. Low fire severity in this case refers to fires that char but do not completely consume leaf litter, and have patches of unburned vegetation and litter (Brown and DeByle 1987). Moderate severity fires consume litter and some duff. Severe fires generally consume all litter and duff.

**Fire Intensity Measure**: Feet. Flame length F or Scorch height S may be used as measures of fire intensity to predict tree mortality.

**Flame Length**: Feet. The average length of the flame. Flame length and flame height are only equal under no-wind, no-slope conditions. Flame length is not computed by FOFEM from fuel and fire weather parameters. Instead, it is input by the user in the Fire Effects Calculator, or computed as it relates to tree mortality goals in the Prescribed Fire Planner.

**Fuel Category**: Natural fuels N are those accumulating from natural processes of mortality, litterfall, and branchfall. Slash fuels S result from harvest activity. Piles P are generally activity fuels, but are differentiated from slash because less duff consumption and more woody fuel consumption typically occur when fuels are piled.

**Herb**: Tons per acre of herbaceous fuel.

**Herbaceous Density**: Typical T, sparse S, or abundant A. Selection determines the default loading of herbaceous fuel.

**Litter**: Tons per acre. Litter is dead surface fuel consisting of freshly fallen needles, leaves, twigs, and bark (Brown 1974).

**Live Crown Ratio**: The ratio between the length of live crown, and the total tree height. A live crown ratio of 0.7 should be entered as 7.

**NFDR TH Hour Moisture**: Percent. This is the moisture index computed by the National Fire Danger Rating System to reflect moisture content of thousand-hour fuels (logs larger than 3 inches in diameter).

**PM2.5**: Lbs per acre. Emission of particulate matter less than 2.5 microns in diameter.

**PM10**: Lbs per acre. Emission of particulate matter less than 10 microns in diameter.

**Regen**: Tons per acre. Fuel loading of conifer regeneration under 6 feet tall.

**Scorch Height**: Feet. The height to which crown foliage is killed.

**Season of Burn**: S spring, M summer, F fall, W winter.

**Shrub**: Tons per acre of shrubs.

**Shrub Density**: Typical T, sparse S, or abundant A. Selection determines default loading of shrub fuels.

**Species Code**: Six-letter species code consisting of the first three letters of the genus and species names (for example, PINPON for *Pinus ponderosa*).

**Tree Crown Biomass Loading**: Typical T, sparse S, or abundant A. Selection determines default loadings of both crown foliage and crown biomass.

**Tree DBH**: Inches. Tree diameter at breast height.

**Tree Height**: Feet. Total tree height.

**Tree Physiological Status**: Dormant D, or actively growing A.

**Tree Regeneration Density**: Typical T, sparse S, or abundant A. Selection determines default loading of regeneration.

**Trees per Acre**: Number of trees per acre in this species per diameter combination.

**Wood 0-1 Inch**: Tons per acre of dead woody fuel 0 to 1 inch in diameter. Includes 1- and 10-hour fuels.

**Wood 1-3 Inch**: Tons per acre of dead woody fuel 1 to 3 inches in diameter, or 100-hour fuels.

**Wood 3+ Code**: Method used to estimate moisture of the 3+ inch woody fuel. M measured, N NFDR TH moisture code, A adjusted NFDR TH moisture code.

**Wood 3+ Inch**: Tons per acre of dead woody fuel larger than 3 inches in diameter (1,000-hour fuels).

# Appendix B—List of Prediction Equations

| Equation | | source |
|---|---|---|
| **Tree mortality equations:** | | |
| 1 | $P_m = 1.0/\ (1.0 + \exp(-1.941 + 6.316\ (1.0 - \exp(-BT)) - .000535\ CK^2))$ | Ryan and Reinhardt 1988 |
| 2 | not currently used | |
| 3 | same as equation 1, except minimum mortality is set to 0.8 | |
| 4 | $CH = FL/1.8$<br>if fire severity is low,<br>$P_m = 1.0/\ (1.0 + \exp\ (-4.407 + .638\ D - 2.134\ CH))$<br>else<br>$P_m = 1.0/\ (1.0 + \exp\ (-2.157 + .218\ D - 3.60\ CH))$ | Brown and DeByle 1987 |
| **Duff equations:** | | |
| 1 | $\%DR = 97.1 - 0.519\ LDM$ , $LDM <= 160\%$<br>$= 13.6$ , $LDM > 160\%$ | Brown and others 1985 |
| 2 | $\%DR = 83.7 - 0.426\ EDM$ | Brown and others 1985 |
| 3 | $\%DR = 114.7 - 4.20\ NFDTH$ | Brown and others 1985 |
| 4 | $\%DR = 89.9 - 0.55\ LDM$ | Harrington 1987 |
| 5 | $DR = 1.028 - 0.0089\ LDM + 0.417\ DPRE$ | Brown and others 1985 |
| 6 | $DR = 0.8811 - 0.0096\ EDM + 0.439\ DPRE$ | Brown and others 1985 |
| 7 | $DR = 1.773 - 0.1051\ NFDTH + 0.399\ DPRE$ | Brown and others 1985 |
| 8 | DR = | Ottmar and others 1993 |

1. first compute diameter reduction DIARED (inches) and large woody fuel consumption (tons per acre)

2. determine whether it is a wet, moist, or dry regime:
   compute days-to-moist = $21\ (DPRE/3)^{1.18}$ = number of days since rain until duff dries to a moist regime.
   compute days-to-dry = $57\ (DPRE/3)^{1.18}$ = number of days since rain until duff reaches a dry regime.

3. compute yadj = minimum value of (DIARED/1.68) and 1.

4. if wet regime:
   $DR = .537\ yadj + 0.057$(large woody fuel consumption)

5. if moist regime:
   $DR = .323\ yadj + 1.034\ DIARED^{0.5}$

6. if dry regime:
   DR = (DR for moist regime) + ((days-since-rain − days-to-dry)/27)

(con.)

7. If preburn duff depth is less than 1", multiply predicted duff reduction by 0.5
If preburn duff depth is between 1 and 2", multiply by 0.75

9 MSE = 80.0 - 0.507 LDM, LDM <= 135% Brown and others 1985
= 23.5 - 0.0914 LDM, LDM > 135%

10 MSE = 167.4 - 31.6 log(EDM) Brown and others 1985

11 MSE = 93.3 - 3.55 NFDTH Brown and others 1985

12 MSE = 94.3 - 4.96 NFDTH Brown and others 1985

13 MSE = 60.4 - 0.440 LDM Brown and others 1985

14 MSE = -8.98 + 0.899 %DR Brown and others 1985

15 RD = -0.791 + .004 EDM + 0.8 DPRE + 0.56 PINE Reinhardt and others 1991

16 W = 3.4958 + 0.3833 WPRE - 0.0237 EDM - 5.6075/WPRE Hough 1978
%DR = 0 if W <= L
= 100 ((W-L)/(WPRE-L)), if W > L

17 %DR = 10% (piles)

18 MSE = 10% (piles)

19 %DR = 100% (chaparral)

20 DR = DPRE - 4 (pocosin) Hungerford 1996
for deep organic soils in the pocosin type, preburn duff depth is defined to be the depth above the water table. This depth is set to be 1" if moisture conditions are wet, 5" if moderate, 14" if dry, and 25" if very dry. These defaults can be changed by changing preburn duff depth. It is assumed that the duff is consumed to within 4" of the water table.

201 %DR (pocosin) Hungerford 1996
It is assumed that the top 8" of the duff is root mat with a bulk density of 0.1, and the muck below has a bulk density of 0.2. Duff loading consumed and percent duff consumption are calculated by assuming that this material burns from the top down to within 4" of the water table.

202 MSE = 0% (pocosin) Hungerford 1996
for deep organic soils in the pocosin type, we assume mineral soil will never be exposed.

Woody fuel equations:

1- and 10-hour fuel consumption:

21 assume 90%

211 assume 100% (100-hour consumption is greater than 90%)

212 assume 100% (piles)

213 assume 100% (SE)

(con.)

<u>100-hour fuel consumption equations:</u>

natural fuels:

25 assume 65% consumption

slash fuels:

261 % consumption = 167.016 - 4.887 MC10 Ottmar and others 1993

261 % consumption = 100 (MC10 < 13.7) Ottmar and others 1993

261 % consumption = 0 (MC10 > 34) Ottmar and others 1993

262 assume 0% consumption (SE broadcast)

263 assume 90% consumption (piles)

<u>Large woody fuel consumption equations:</u>

slash fuels:

27 DIARED = 1.319 - 0.096 MC + 0.607 PDIA Brown and others 1991

28 DIARED = 4.6495 - 0.096 ADJTH (spring-like) Ottmar and others 1993

28 DIARED = 6.27 - 0.125 ADJTH (ADJTH < 44%) Ottmar and others 1993

28 DIARED = 1.499- 0.0178 ADJTH (44<=ADJTH<=60) Ottmar and others 1993

28 DIARED = 0.731 - 0.005 ADJTH (ADJTH > 60%) Ottmar and others 1993

29 DIARED = 6.17 - 0.117 ADJTH Brown and others 1991

natural fuels:

31 DIARED = 1.114 - 0.027 MC + 0.454 PDIA - 1.532 SEASON
Brown and others 1991

32 DIARED = 7.917 - 0.252 ADJTH + 0.34 PDIA Brown and others 1991

33 Same as 32 except use 1.4 (NFDTH) instead of ADJTH
Brown and others 1991

34 Same as 28 except use 1.4 (NFDTH) instead of ADJTH
Ottmar and others 1993

35 Same as 29 except use 1.4 (NFDTH) instead of ADJTH
Brown and others 1991

Piles:

36 % consumption = 90%

For equations 27, 28 and 29, predicted diameter reduction should be reduced if fire intensity is greater than moderate. Intense fires are thought to go out quicker, actually resulting in less consumption of large fuel. This is for slash fires only, in the Pacific West or Interior West. Reduction factors are:

| intensity | % reduction in predicted diameter reduction |
|---|---|
| extreme | 33 |

(con.)

```
very high       22
high            11
```

Loading consumed and percent consumption will be computed from diameter reduction, preburn diameter, and preburn loading.

Fraction consumed = 1 - ((PDIA - DIARED)/PDIA)$^2$

Adjustments should be made to the moisture inputs in some situations:

1 slash fuels are uncured:
    instead of using ADJTH,
    use 119.64 exp(-0.0069(days-since-harvest))

2 User chooses NFDR 1000 hr moisture instead of ADJTH:
    compute ADJTH = 1.4 (NFDRTH)

<u>Other fuels:</u>

<u>Herbs:</u>

22 assume 100% consumption

221 assume 90% consumption

<u>Shrubs:</u>

23 assume 60% consumption

231 assume a level of shrub consumption so that total fuel consumption = 80%, while duff, litter, and herb consumption are 100% (chaparral)

232 assume 50% consumption (sagebrush, spring)

233 assume 90% consumption (sagebrush, fall; pocosin, spring and winter)

234 percent consumption =(((3.2484 + 0.4322 WPRE + .6765 (SHRUB+REGEN) - 0.0276 EDM - 5.0796/WPRE) - W)/(SHRUB+REGEN))*100%)
(W is from eq 16) (southeast)

235 assume 80% consumption (pocosin, summer and fall)

<u>Regen:</u>

24 assume 60% consumption

241 same as 234

<u>Canopy foliage:</u>

37 assume 100% consumption

<u>Canopy fine branchwood:</u>

38 assume 50% consumption

<u>Litter:</u>

39 assume 100% consumption

(con.)

40 = (W/L) 100%, if W <= L (W from eq 16)
= 100% if W>L

41 assume 10% consumption

42 assume 50% consumption

<u>Equation term definitions:</u>
DIARED = diameter reduction of large woody pieces, inches
DAYS-SINCE-RAIN = number of days since significant rain (0.5 inches west of the cascades and 0.25 inches east of the cascades)
DAYS-SINCE-HARVEST = days without snow since harvest. If greater than 90, fuels are cured.
RD = residual duff depth, in
PINE = 1 if long needle type, 0 otherwise
WPRE = preburn loading of forest floor (litter plus duff), t/ac
L = preburn loading of litter, t/ac
W = loading of forest floor (litter plus duff) consumed, t/ac
D = preburn loading of rootmass and muck above the water table, t/ac (pocosin)
DR = duff depth reduction, in
%DR = duff depth reduction, percent
MSE = percent mineral soil exposure
LDM = lower duff moisture, percent
EDM = entire duff moisture, %
NFDTH = nfdrs 1000 hour moisture content
DPRE = preburn duff depth, inches
MC = actual large log moisture content
PDIA = quadratic mean preburn diameter, in
SEASON = 1 if spring, 0 otherwise
ADJTH = adjusted nfdrs 1000 hour moisture: user should be able to enter this directly or enter NFDTH and the program will estimate ADJTH.
SHRUB = preburn shrub load, t/ac
REGEN = preburn regen load, t/ac
MC10 = moisture content of 10 hour woody fuel, %
INTENSITY = fire intensity: extreme, very high, high, moderate, low
$P_m$ = probability of mortality
BT = bark thickness, inches
CK = crown volume killed, %
D = diameter, inches
CH = char height, feet
FL = flame length, feet

## Appendix C—Decision Key for Selecting Fuel Algorithms

**Duff, Mineral Soil, and Litter Equation Key**

```
1. Piles, all geographic regions
      %DR    EQ 17
      MSE    EQ 18
      litter EQ 41
1. not piled
      2. interior West
            litter EQ 39
            3. slash
                        %DR    LDM    EQ 1
                               EDM    EQ 2
                               NFDTH  EQ 3
                        DR     LDM    EQ 5
                               EDM    EQ 6
                               NFDTH  EQ 7
                        MSE    LDM    EQ 9
                               EDM    EQ 10
                               NFDTH  EQ 11
            3. natural fuel
                  4. ponderosa pine
                        %DR    LDM    EQ 4
                               EDM    EQ 2
                               NFDTH  EQ 3
                        DR     LDM    EQ 5
                               EDM    EQ 6
                               NFDTH  EQ 7
                        MSE    LDM    EQ 13
                               EDM    EQ 10
                               NFDTH  EQ 12
                  4. other cover types
                        %DR    LDM    EQ 1
                               EDM    EQ 2
                               NFDTH  EQ 3
                        DR     LDM    EQ 5
                               EDM    EQ 6
                               NFDTH  EQ 7
                        MSE    LDM    EQ 13
                               EDM    EQ 10
                               NFDTH  EQ 12
      2. Pacific Northwest
                  5. natural fuels
                        6. ponderosa pine
                               %DR    LDM    EQ 4
                               EDM    EQ 2
                               NFDTH  EQ 3
                               DR     LDM    EQ 5
                               EDM    EQ 6
                               NFDTH  EQ 7
                               MSE    LDM    EQ 13
                               EDM    EQ 10
                               NFDTH  EQ 12
                        6. other cover types
                               %DR    LDM    EQ 1
                               EDM    EQ 2
                               NFDTH  EQ 3
                               DR     LDM    EQ 5
                               EDM    EQ 6
                               NFDTH  EQ 7
```

```
                              MSE    LDM    EQ 13
                              EDM    EQ 10
                              NFDTH  EQ 12

          5. slash
               litter EQ 39
               DR     EQ 8
               %DR    compute from EQ 8 and preburn depth
               MSE    EQ 14
     2. North East
          litter EQ 39
          7. Jack pine, red pine
               DR     EDM    compute from EQ 15 and preburn depth
                      NFDTH EQ 3 and preburn depth
               DR%    EDM    compute from EQ 15 and preburn depth
                      NFDTH EQ 3
               MSE    EDM    EQ 15 and EQ 14
                      NFDTH  EQ 3 and EQ 14
          7. White pine
               use Interior West Key
          7. Balsam fir, spruce
               DR     LDM    EQ 5
                      EDM    EQ 15 and preburn depth
                      NFDTH  EQ 3
               %DR    LDM    compute from EQ 5 and preburn depth
                      EDM    EQ 15 and preburn depth
                      NFDTH  EQ 3
               MSE    LDM    EQ 5 and EQ 14
                      EDM    EQ 15 and 14
                      NFDTH  EQ 3 and EQ 14
     2. Southeast
     3. pocosin
          DR     EQ 20
          %DR    EQ 201
          MSE    EQ 202
          4. wet moisture conditions
               litter EQ 42
          4. other moisture conditions
               litter EQ 39
     3. other cover types
          %DR    EQ 16
          MSE    EQ 14
          litter EQ 40
```

## Woody Fuel Consumption Equation Key

```
1 & 10 hour woody fuel
1. Southeast
          EQ 213
1. All other regions
     2. Piles
               EQ 212
     2.   Natural or Slash fuels
          3. 100 hour consumption < 90 percent
                    EQ 21
          3. 100 hour consumption > 90 percent
                    EQ 211
100 hour woody fuel
1. natural fuel
     2. Southeast region
          EQ 262
     2. All other regions
          EQ 25
```

1. piles (all geographic regions)
EQ 263
1. slash (broadcast)
3. Southeast region
EQ 262
3. All other regions
EQ 261
1000 hour woody fuels
1. Piles (all geographic regions)
EQ 36
1. Natural Fuels (all geographic regions)
measured moisture EQ 31
adj th hr EQ 32
1. Slash
measured moisture EQ 27
adj-th
2. Pacific Northwest
EQ 28
2. Interior West
EQ 29
2. Southeast
has no 1000 hour fuels in current models
2. Northeast
currently has no slash models

**Other fuels**
herbs
1. grasslands
2. summer EQ 221
2. other seasons EQ 22
1. other cover types EQ 22
shrubs
1. Southeastern Region
2. pocosin
3. spring and winter EQ 233
3. summer and fall EQ 235
2. other cover types EQ 234
1. Other Regions
2. Sagebrush
3. Spring
EQ 232
3. Fall
EQ 233
2. Chaparral, desert shrub, shinnery, sw shrub-steppe, texas savannah
EQ 231
2. Any other cover type
EQ 23
regen
1. Southeastern Region
EQ 241
1. All other regions
EQ 24
canopy foliage
EQ 37
canopy branchwood
EQ 38

## Appendix D—Tree Species Available in FOFEM

| Species code | Mortality equation[a] | Bark equation[b] | Height equation[c] | Crown ratio | Geog region[d] |
|---|---|---|---|---|---|
| ABIAMA *Abies amabilis*—Pacific silver fir | 1 | 7 | 7 | 8 | 2 |
| ABIBAL *Abies balsamea*—Balsam fir | | | | | 1 3 |
| ABICON *Abies concolor*—White fir | 1 | 4 | 4 | 7 | 1 2 |
| ABIGRA *Abies grandis*—Grand fir | 1 | 4 | 4 | 7 | 1 2 |
| ABILAS *Abies lasiocarpa*—Subalpine fir | 1 | 7 | 7 | 8 | 1 2 |
| ABIMAG *Abies magnifica*—Red fir | | | | | 1 2 |
| ABIPRO *Abies procera*—Noble fir | 1 | 7 | 7 | 8 | 2 |
| CHALAW *Chamaecyparis lawsoniana* Port-Orford-cedar | 1 | 10 | 10 | 7 | 2 |
| CHANOO *Chamaecyparis nootkatensis*—Alaska-cedar | 1 | 10 | 10 | 7 | 2 |
| LARLYA *Larix lyallii*—Subalpine larch | | | | | 1 |
| LAROCC *Larix occidentalis*—Western larch | 1 | 3 | 3 | 4 | 1 |
| LIBDEC *Libocedrus decurrens*—Incense-cedar | 1 | 4 | 4 | 7 | 1 2 |
| PICENG *Picea engelmannii*—Engelmann spruce | 3 | 10 | 10 | 7 | 1 2 |
| PICGLA *Picea glauca*—White spruce | 3 | 10 | 10 | 7 | 1 2 3 |
| PICMAR *Picea mariana*—Black spruce | 3 | 10 | 10 | 7 | 1 2 3 |
| PICPUN *Picea pungens*—Blue spruce | 3 | 10 | 10 | 7 | 1 |
| PICRUB *Picea rubens*—Red spruce | 3 | 10 | 10 | 7 | 3 4 |
| PICSIT *Picea sitchensis*—Sitka spruce | 3 | 10 | 10 | 7 | 2 |
| PINALB *Pinus albicaulis*—Whitebark pine | 1 | 9 | 9 | 5 | 1 2 |
| PINBAN *Pinus banksiana*—Jack pine | 1 | 8 | 8 | 4 | 1 3 |
| PINCON *Pinus contorta*—Lodgepole pine | 1 | 8 | 8 | 4 | 1 2 |
| PINFLE *Pinus flexilis*—Limber pine | | | | | 1 |
| PINJEF *Pinus jeffreyi*—Jeffrey pine | 1 | 1 | 1 | 4 | 1 2 |
| PINLAM *Pinus lambertiana*—Sugar pine | 1 | 12 | 12 | 5 | 1 2 |
| PINMON *Pinus monticola*—Western white pine | 1 | 12 | 12 | 5 | 1 2 |
| PINPON *Pinus ponderosa*—Ponderosa pine | 1 | 1 | 1 | 4 | 1 2 |
| PINRES *Pinus resinosa*—Red pine | | | | | 3 |
| PINSTR *Pinus strobus*—Eastern white pine | 1 | 12 | 12 | 5 | 3 4 |
| POPTRE *Populus tremuloides*—Quaking aspen | 4 | 11 | 11 | 4 | 1 2 3 |
| PSEMEN *Pseudotsuga menziesii*—Douglas-fir | 1 | 2 | 2 | 7 | 1 2 |
| SEQGIG *Sequoia gigantea*—Giant sequoia | | | | | 2 |
| SEQSEM *Sequoia sempervirens*—Redwood | | | | | 2 |
| TAXBRE *Taxus brevifolia*—Pacific yew | 1 | 7 | 7 | 8 | 1 2 |
| THUPLI *Thuja plicata*—Western redcedar | 1 | 5 | 5 | 8 | 1 2 |
| TSUHET *Tsuga heterophylla*—Western hemlock | 1 | 6 | 6 | 8 | 1 2 |
| TSUMER *Tsuga mertensiana*—Mountain hemlock | 1 | 6 | 6 | 8 | 1 2 |

[a]Mortality equations are listed in appendix B.
[b]Bark thickness equations are listed in table 1.
[c]Tree height equations are listed in table 2.
[d]Geographic regions: 1 = Interior West, 2 = Pacific West, 3 = North East, 4 = South East.

## Appendix E—Cover Types

| No. | Cover type | Geographic region[a] |
|---|---|---|
| 101 | Jack pine (SAF 1) | 2 3 |
| 102 | Red pine (SAF 15) | 3 |
| 103 | White pine (SAF 21) | 3 4 |
| 104 | White pine-hemlock (SAF 22) | 3 4 |
| 105 | Hemlock (SAF 23) | 3 4 |
| 111 | Balsam fir (SAF 5) | 3 |
| 112 | Black spruce (SAF 12,204) | 1 2 3 |
| 113 | Red spruce-balsam fir (SAF 33) | 3 4 |
| 114 | Black spruce-tamarack (SAF 13) | 3 |
| 115 | Red spruce (SAF 32) | 3 |
| 116 | White spruce (SAF 107,201) | 1 2 3 |
| 120 | Longleaf-slash pine (SAF 83) | 4 |
| 121 | Longleaf pine (SAF 70) | 4 |
| 122 | Slash pine (SAF 84) | 4 |
| 130 | Lobolly-shortleaf pine (SAF 80) | 4 |
| 131 | Lobolly pine coastal (SAF 81) | 4 |
| 301 | Loblolly pine piedmont (SAF 81) | 4 |
| 132 | Shortleaf pine (SAF 75) | 4 |
| 133 | Virginia pine (SAF 79) | 3 4 |
| 134 | Sand pine (SAF 69) | 4 |
| 136 | Pond pine (SAF 98) | 4 |
| 025 | Pond pine pocosin | 4 |
| 138 | Pitch pine (SAF 45) | 3 |
| 140 | Oak pine (FRES 14) | 3 4 |
| 141 | White pine-northern red oak-white ash (SAF 20) | 3 4 |
| 143 | Longleaf pine-scrub oak (SAF 71) | 4 |
| 144 | Shortleaf pine-oak (SAF 76) | 4 |
| 145 | Virginia pine-southern red oak (SAF 78) | 4 |
| 146 | Lobolly pine-oak (SAF 82) | 4 |
| 147 | Slash pine-hardwood (SAF 85) | 4 |
| 150 | Oak hickory (FRES 15) | 3 4 |
| 151 | Post, black, or bear oak (SAF 40,43) | 3 4 |
| 152 | Chestnut oak (SAF 44) | 3 4 |
| 154 | White oak (SAF 53) | 3 4 |
| 155 | Northern red oak (SAF 55) | 3 4 |
| 156 | Yellow poplar-white oak-northern red oak (SAF 59) | 3 4 |
| 190 | Aspen-birch (FRES 19) | 2 3 |
| 191 | Aspen (SAF 16) | 2 3 |
| 192 | Paper birch (SAF 18) | 1 2 3 |
| 194 | Paper birch (SAF 252) | 1 2 |
| 200 | Douglas-fir (SAF 229) Pacific | 2 |
| 201 | Douglas-fir (SAF 210) Interior | 1 2 |
| 202 | Douglas-fir-western hemlock (SAF 230) | 2 |
| 203 | Port-Orford-cedar-Douglas-fir (SAF 231) | 2 |
| 210 | Ponderosa pine (SAF 245) Pacific | 2 |
| 211 | Ponderosa pine (SAF 237) Interior | 1 2 |
| 212 | Jeffrey pine (SAF 247) | 1 2 |
| 213 | Sierra Nevada mixed conifer (SAF 243) | 2 |

(con.)

| No. | Cover type | Geographic region[a] |
|---|---|---|
| 221 | Western white pine (SAF 215) | 1 |
| 230 | Fir-spruce (FRES 23) | 2 |
| 231 | White fir (SAF 211) | 1 2 |
| 232 | Red fir (SAF 207) | 2 |
| 234 | Coastal true fir (SAF 226) | 2 |
| 236 | Englemann spruce subalpine fir (SAF 206) | 1 2 |
| 237 | Blue spruce (SAF 216) | 1 |
| 238 | Douglas-fir-tanoak (SAF 234) | 2 |
| 240 | Hemlock-sitka spruce (SAF 225) (FRES 24) | 2 |
| 241 | Western redcedar (SAF 228) | 2 |
| 242 | Sitka spruce (SAF 223) | 2 |
| 247 | Mountain hemlock-subalpine fir (SAF 205) | 1 2 |
| 248 | Western hemlock (SAF 224) | 1 2 |
| 250 | Larch (SAF 212) | 1 |
| 255 | Larch-Douglas-fir (SAF 212) | 1 |
| 256 | Grand fir-larch-Douglas-fir | 1 |
| 257 | Ponderosa pine-Douglas-fir (SAF 244) | 2 |
| 258 | Grand fir (SAF 213) | 1 |
| 260 | Lodgepole pine (SAF 218) | 1 2 |
| 271 | Redwood (SAF 232) | 2 |
| 283 | Aspen (SAF 217) | 1 2 |
| 284 | California black oak (SAF 246) | 2 |
| 293 | Pinyon-juniper (FRES 35) | 1 2 |
| 295 | Bristlecone pine (SAF 209) | 1 |
| 296 | Whitebark pine (SAF 208) | 1 2 |
| 002 | Desert grasslands (FRES 40) | 1 |
| 003 | Plains grasslands (FRES 38) | 1 4 |
| 004 | Mountain grasslands (FRES 36) | 1 2 |
| 005 | Mountain meadows (FRES 37) | 1 2 |
| 006 | Prairie—tall grass (FRES 39) | 1 3 4 |
| 007 | Wet grasslands (FRES 41) | 1 2 3 4 |
| 008 | Sagebrush—low shrub cover (FRES 29) | 1 2 |
| 009 | Sagebrush—moderate shrub cover (FRES 29) | 1 2 |
| 010 | Sagebrush—high shrub cover (FRES 29) | 1 2 |
| 011 | Chaparral—low shrub cover (FRES 34) | 1 2 |
| 012 | Chaparral—moderate shrub cover (FRES 34) | 1 2 |
| 013 | Chaparral—high shrub cover (FRES 34) | 1 2 |
| 014 | Desert Shrub—low shrub cover (FRES 30) | 1 |
| 015 | Desert Shrub—moderate shrub cover (FRES 30) | 1 |
| 016 | Desert Shrub—high shrub cover (FRES 30) | 1 |
| 017 | Shinnery—low shrub cover (FRES 31) | 1 |
| 018 | Shinnery—moderate shrub cover (FRES 31) | 1 |
| 019 | Shinnery—high shrub cover (FRES 31) | 1 |
| 020 | SW Shrub Steppe—low shrub cover (FRES 33) | 1 |
| 021 | SW Shrub Steppe—moderate shrub cover (FRES 33) | 1 |
| 022 | SW Shrub Steppe—high shrub cover (FRES 33) | 1 |
| 023 | Texas Savannah (FRES-32) | 1 4 |

[a]Geographic regions: 1 = Interior West, 2 = Pacific West, 3 = North East, 4 = South East.

## Appendix F—Fuel Models

### Development of Default Fuel Models for FOFEM

Fuel loading models were developed for Society of American Foresters cover types (Eyre 1980) for applying to forested areas and Forest-Range Environmental Study (FRES) ecosystem types (Garrison and others 1977) for applying to shrub and grassland areas. The fuel models were extended to other vegetation types whenever fuels were thought to be similar. (Fuel model vegetation types and equivalent vegetation types assumed to have the same fuels are given below. All type names are SAF cover types unless specified otherwise.)

| Fuel model | Equivalent types |
|---|---|
| Interior ponderosa pine | — |
| Jeffrey pine | Pacific ponderosa pine |
| Interior Douglas-fir | Western larch, larch-Douglas-fir, grand fir-larch-Douglas-fir |
| Western white pine | — |
| Blue spruce | — |
| Engelmann spruce-subalpine fir | Red fir, white fir, fir-spruce (FRES 23), mountain hemlock-subalpine fir |
| Sierra Nevada mixed conifer | Ponderosa pine-Douglas-fir, California black oak |
| Grand fir | — |
| Lodgepole pine | — |
| Whitebark pine | Bristlecone pine |
| Black spruce (SAF 204) | Black spruce (SAF 12), balsam fir, black spruce-tamarack, black spruce-paper birch |
| White spruce (SAF 201) | Red spruce, red spruce-balsam fir, white spruce (SAF 107) |
| Douglas-fir, western hemlock | Redwood, w. hemlock, Sitka spruce, w. redcedar, w. hemlock-Sitka spruce, coastal true fir-hemlock, Pacific Douglas-fir, hemlock-Sitka spruce (FRES 24), Port Orford cedar-Douglas-fir |
| Aspen (SAF 217) | Paper birch (SAF 252) |
| Aspen (SAF 16) | Paper birch (SAF 18), aspen-birch (FRES 19) |
| Jack pine | Pitch pine |
| Red pine | — |
| Eastern white pine | White pine-eastern hemlock, e. hemlock |
| Shortleaf pine | — |
| Virginia pine | — |
| Pond pine | — |
| Black oak | Oak-hickory (FRES 15), northern red oak, post oak-blackjack oak, northern pin oak, white oak, chestnut oak, bear oak, bur oak, yellow poplar-white oak, northern red oak |
| Oak-pine (FRES 14) | Shortleaf pine-oak, Virginia pine-southern red oak, white pine-northern red oak-white ash |
| Loblolly pine (Piedmont) | Loblolly pine-shortleaf pine, loblolly pine-oak, slash pine-hardwood |
| Longleaf pine | — |
| Slash pine | Longleaf-slash pine, sand pine |
| Loblolly pine (coastal) | — |
| Pinyon-juniper (FRES 35) | Pinyon-juniper, Rocky Mountain juniper, western juniper, Arizona cypress |
| Chaparral (FRES 34) | — |
| Sagebrush (FRES 29) | Shinnery (FRES 31) |
| Desert shrub (FRES 30) | — |
| SW shrub steppe (FRES 33) | — |
| Texas savannah (FRES 32) | — |
| Desert grasslands (FRES 40) | — |
| Plains grasslands (FRES 38) | — |
| Mountain grasslands (FRES 36) | — |
| Mountain meadows (FRES 37) | — |
| Tall grass prairie (FRES 39) | — |
| Wet grasslands (FRES 41) | — |

Table 5—Fuel models for forest types and references used in constructing the models.

| Type | Classification | Litter | Downed woody 0-1 | Downed woody 1-3 | Downed woody 3+ | Duff | Herbaceous S | Herbaceous A | Shrub S | Shrub A | Regeneration S | Regeneration A | Duff depth | References[a] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | - - - - - | - - - - - | - - - - - | - - - - - | Tons per acre | - - - - - | - - - - - | - - - - - | - - - - - | - - - - - | - - - - - | inches | |
| Interior ponderosa pine | SAF 237 | 1.4 | 0.7 | 0.8 | 5 | 5 | 0.1 | 0.3 | 0 | 0.5 | 0 | 0.3 | 0.6 | 1,2,3,4 |
| Jeffrey pine | SAF 247 | 1.5 | 1.0 | 1.0 | 10 | 25 | 0.1 | 0.3 | 0 | 0.5 | 0 | 0.3 | 2.0 | 5,10 |
| Interior Douglas-fir | SAF 210 | 0.6 | 0.9 | 0.8 | 7 | 10 | 0.1 | 0.3 | 0 | 0.4 | 0 | 0.3 | 1.0 | 2,6 |
| Western white pine | SAF 215 | 0.8 | 1.0 | 0.8 | 40 | 30 | 0.1 | 0.2 | 0 | 0.2 | 0 | 0.3 | 2.0 | 2,6,10 |
| Douglas-fir-tan oak-Pacific madrone | SAF 234 | 1.0 | 2.1 | 1.7 | 10 | 10 | 0.1 | 0.3 | 0 | 0.2 | 0 | 0.3 | — | 7 |
| Blue spruce | SAF 216 | 1.0 | 0.9 | 1.3 | 20 | 20 | 0.1 | 0.2 | 0 | 0.2 | 0 | 0.3 | 1.1 | 4 |
| Engelmann spruce-subalpine fir | SAF 206 | 0.6 | 1.1 | 1.1 | 20 | 30 | 0.1 | 0.2 | 0 | 0.4 | 0 | 0.3 | 1.6 | 2,6,8 |
| Grand fir | SAF 213 | 0.6 | 0.7 | 1.5 | 14 | 25 | 0.1 | 0.2 | 0 | 0.2 | 0 | 0.3 | 1.4 | 2,6 |
| Sierra Nevada mixed conifer | SAF 243 | 1.5 | 1.0 | 1.5 | 20 | 40 | 0.1 | 0.3 | 0 | 0.5 | 0 | 0.3 | 3.0 | 5,10 |
| Lodgepole pine | SAF 218 | 0.6 | 0.9 | 0.6 | 15 | 15 | 0.1 | 0.3 | 0 | 0.2 | 0 | 0.3 | 1.1 | 2,6 |
| Whitebark pine | SAF 208 | 0.3 | 0.7 | 0.5 | 7 | 10 | 0.1 | 0.3 | 0 | 0.5 | 0 | 0.3 | 0.8 | 2 |
| Aspen | SAF 217 | 0.9 | 1.0 | 1.5 | 7 | 5 | 0.2 | 0.5 | 0 | 0.5 | 0 | 0.3 | 0.6 | 9 |
| Aspen | SAF 16 | 0.9 | 1.0 | 1.0 | 3 | 5 | 0.2 | 0.4 | 0 | 1.0 | 0 | 0.2 | 0.6 | 9 |
| Jack pine | SAF 1 | 0.7 | 1.1 | 0 | 3 | 34 | 0.1 | 0.2 | 0 | 0.2 | 0 | 0.3 | 2.5 | 11,12,13 |
| Red pine | SAF 15 | 1.1 | 1.6 | 0 | 3 | 12 | 0.1 | 0.2 | 0 | 0.2 | 0 | 0.3 | 1.5 | 11 |
| Eastern white pine | SAF 21 | 0.7 | 1.1 | 0 | 3 | 11 | 0.1 | 0.2 | 0 | 0.2 | 0 | 0.3 | 1.7 | 14,16 |
| Black spruce | SAF 204 | 13.9 | 0 | 0 | 0 | 50 | 0.1 | 0.2 | 0 | 0.2 | 0 | 0.3 | 3.8 | 15 |
| White spruce | SAF 201 | 11.1 | 0 | 0 | 0 | 35 | 0.1 | 0.2 | 0 | 0.2 | 0 | 0.3 | 2.3 | 15 |
| Douglas-fir-western hemlock | SAF 230 | 1.0 | 2.2 | 2.6 | 50 | 35 | 0.1 | 0.3 | 0 | 0.4 | 0 | 0.3 | 2.0 | 7,21,22,23 |
| Shortleaf pine | SAF 75 | 1.1 | 0 | 0 | 0 | 6 | 0 | 0.2 | 0 | 0.2 | 0 | 0.3 | 0.6 | 16,17 |
| Virginia pine | SAF 79 | 1.1 | 0 | 0 | 0 | 6 | 0 | 0.2 | 0 | 0.2 | 0 | 0.3 | 0.6 | 16 |
| Pond pine | SAF 98 | 0.7 | 0 | 0 | 0 | 3.8 | 1.0 | 2.4 | 1.4 | 3.6 | 0 | 0.3 | — | 18 |
| Black oak | SAF 110 | 2.0 | 0.5 | 0 | 0 | 4 | 0 | 0.1 | 0 | 0.2 | 0 | 0.1 | 0.8 | 19,20 |
| Oak-pine | FRES 14 | 0.9 | 0 | 0 | 0 | 5.7 | 0 | 0 | 2.8 | 4.7 | 0 | 0.3 | — | 24 |

[a]Authors keyed to reference number are: 1. Brown 1970, 2. Brown and Bevins 1986, 3. Brown and See 1981, 4. Sackett 1979, 5. Kauffmann and Martin 1989, 6. Brown and Bradshaw 1994, 7. Maxwell and Ward 1980, 8. Taylor and Fonda 1990, 9. Brown and Simmerman 1986, 10. Woolridge 1970, 11. Brown 1966, 12. Walker and Stocks 1975, 13. Quintilio and others 1977, 14. Mader and Lull 1968, 15. Barney and others 1981, 16. Metz and others 1970, 17. Crosby 1961, 18. Wendell and others 1962, 19. Crosby and Loomis 1974, 20. Loomis 1975, 21. Little and others 1986, 22. Williams and Dyrness 1967, 23. Kilgore 1972, 24. Southern Forest Fire Laboratory staff 1976.

## Forest Ecosystems

Fuel models for a representation of cover types across the United States are shown in table 5. Fuel loadings were derived by reviewing the literature on fuels and using judgement to determine values that might be typically encountered in each vegetation type. To introduce variability into fuel models, adjustment factors were assigned to each fuel component. Dead fuel adjustments were based on ratios of median-to-mean for lighter than average and third quartile-to-mean for heavier than average. Dead fuel factors were:

| | Litter | Small woody | Large woody | Duff |
|---|---|---|---|---|
| Lighter | 0.5 | 0.7 | 0.4 | 0.6 |
| Heavier | 1.2 | 1.3 | 1.6 | 1.4 |

For live fuels, sparse and abundant loadings were established. The typical condition generally was assumed to be the midpoint between sparse and abundant. Duff loadings were largely determined from data on duff depth and bulk densities of duff, which ranged from 5 to 10 $lb/ft^3$.

Considerable resolution in fuel loading tables was developed for the major southern pine types by including age of rough as a variable (table 6). The southern pine models were based on fuel loading tables developed by the Southern Forest Fire Laboratory Staff (1976) and research on fuel component fractions by McNab and others (1978) and Boyer and Fahnestock (1966). The southern pine fuel groups were formed based on similarity of understory fuels according to the experience of Dale Wade, Southern Research Station, Macon, GA.

For assessing fuel consumption during crown fires, crown fuel loadings were determined from estimates of typical stand densities and crown weight relationships by Brown (1978).

**Table 6**—Southern pine fuel models for natural stands and plantations[a].

| Type | Age of rough | Litter | Duff | Herbaceous Natural S | Herbaceous Natural A | Herbaceous Plantation S | Herbaceous Plantation A | Shrubs[b] natural S | Shrubs[b] natural A |
|---|---|---|---|---|---|---|---|---|---|
| | *year* | *Tons per acre* | | | | | | | |
| Longleaf pine (SAF 70) | 1 | 2.10 | 0 | 1.00 | 1.90 | 1.00 | 1.90 | 0 | 0 |
| | 2 | 1.92 | 1.58 | .50 | 1.00 | .50 | 1.00 | 0 | 0 |
| | 3 | 1.54 | 3.26 | .35 | .71 | .35 | .71 | 0 | 0 |
| | 5 | 1.22 | 5.58 | .24 | .48 | .24 | .48 | 0 | 0 |
| | 10 | 1.39 | 8.51 | .15 | .31 | .15 | .31 | 0 | 0 |
| | 15 | 1.58 | 9.72 | .13 | .26 | .13 | .26 | 0 | 0 |
| Slash pine (SAF 84) | 1 | 2.10 | 0 | 0 | 0 | 0.25 | 0.50 | 0.7 | 1.1 |
| | 2 | 1.92 | 1.58 | 0 | 0 | .12 | .25 | 1.0 | 1.6 |
| | 3 | 1.54 | 3.26 | 0 | 0 | .06 | .17 | 1.2 | 2.0 |
| | 5 | 1.22 | 5.58 | 0 | 0 | 0 | .12 | 1.6 | 2.7 |
| | 10 | 1.39 | 8.51 | 0 | 0 | 0 | .07 | 2.8 | 4.7 |
| | 15 | 1.58 | 9.72 | 0 | 0 | 0 | .06 | 4.0 | 6.6 |
| Loblolly pine (SAF 81) (coastal) | 1 | 1.90 | 0 | 0 | 0 | 0.25 | 0.50 | 0.7 | 1.1 |
| | 2 | 1.65 | 1.35 | 0 | 0 | .12 | .25 | 1.0 | 1.6 |
| | 3 | 1.31 | 2.79 | 0 | 0 | .06 | .17 | 1.2 | 2.0 |
| | 5 | .97 | 4.43 | 0 | 0 | 0 | .12 | 1.6 | 2.7 |
| | 10 | .92 | 5.68 | 0 | 0 | 0 | .07 | 2.8 | 4.7 |
| | 15 | .92 | 5.68 | 0 | 0 | 0 | .06 | 4.0 | 6.6 |
| Loblolly pine (SAF 81) (Piedmont) | 1 | 1.90 | 0 | 0 | 0 | 0 | 0.25 | 0.35 | 0.7 |
| | 2 | 1.65 | 1.35 | 0 | 0 | 0 | .12 | .5 | 1.0 |
| | 3 | 1.31 | 2.79 | 0 | 0 | 0 | .08 | .6 | 1.2 |
| | 5 | .97 | 4.43 | 0 | 0 | 0 | .06 | .8 | 1.6 |
| | 10 | .92 | 5.68 | 0 | 0 | 0 | 0 | 1.4 | 2.8 |
| | 15 | .92 | 5.68 | 0 | 0 | 0 | 0 | 2.0 | 4.0 |

[a]Regeneration loadings for all models are 0 (sparse) and 0.3 (abundant).
[b]Shrub loadings are assumed to be 0 in all plantations.

Residue loadings were based primarily on knowledge of slash loadings created by harvesting and crown component fractions from research by Brown (1978) and Johansen and McNab (1977). Residue loadings were assigned to all SAF cover types, except for southern pines, based on species groups in table 7. The debris loadings in table 8 were added to the precutting fuel models for southern pines.

The default value for average diameter of large woody fuel (3+ inches) was based on a large number of diameter measurements taken on logging residues comprised of ponderosa pine, Douglas-fir, western larch, lodgepole pine, subalpine fir, and Engelmann spruce.

**Table 7**—Harvesting debris loadings by three species groups[a] based on western conifer crown relationships.

| | Group A Mean | Group A Heavier | Group A Lighter | Group B Mean | Group B Heavier | Group B Lighter | Group C Mean | Group C Heavier | Group C Lighter |
|---|---|---|---|---|---|---|---|---|---|
| | *Tons per acre* | | | | | | | | |
| Litter | 2.5 | 3.0 | 2.0 | 1.5 | 2.0 | 1.0 | 2.0 | 2.5 | 1.5 |
| Woody 0-1 inch | 5.0 | 7.5 | 2.5 | 7.0 | 10.0 | 4.0 | 7.0 | 10.0 | 4.0 |
| Woody 1-3 inches | 8.0 | 12.0 | 4.0 | 12.0 | 17.0 | 7.0 | 8.0 | 11.0 | 5.0 |
| Woody 3+ inches | 12.0 | 22.0 | 2.0 | 15.0 | 25.0 | 5.0 | 20.0 | 30.0 | 10.0 |

[a]Group A: ponderosa pine; Group B: lodgepole pine, subalpine fir, whitebark pine; Group C: Douglas-fir, western larch, grand fir, western redcedar, Engelmann spruce.

**Table 8**—Southern pine debris fuel loadings for addition to precutting fuel models.

| Age of rough | Longleaf and loblolly pine | | | Slash pine | | |
|---|---|---|---|---|---|---|
| | | Woody | | | Woody | |
| | Litter | 0-1 | 1-3 | Litter | 0-1 | 1-3 |
| *Year* | *Tons per acre* | | | | | |
| 1 | 3.0 | 3.3 | 3.0 | 5.0 | 5.4 | 4.6 |
| 2 | 2.1 | 2.3 | 2.1 | 3.6 | 4.0 | 3.4 |
| 3 | 1.3 | 1.4 | 1.3 | 2.3 | 2.5 | 2.2 |
| 5 | 0.3 | 0.4 | 0.3 | 0.6 | 0.7 | 0.7 |

## Shrubland and Grassland Ecosystems

Grass fuel loadings for all shrubland and grassland models (table 9) were determined for three productivity levels based on the productivity classes reported for FRES ecosystem types (Garrison and others 1977). Grass fuel loadings were comprised of current production plus litter from previous years. Litter quantities were calculated from FRES estimates of current production and ratios of litter-to-current production, which ranged from 0.25 to 0.50. The litter-to-current production ratios were based on findings of Redman and others (1993), Hulbert (1988), and Wright and Bailey (1982).

Sagebrush loadings were based on percent cover of big sagebrush (*Artemisia tridentata* ssp. *wyomingensis* and ssp. *vaseyana*) averaging about 2 feet in height (Brown 1982). Grass loadings were modeled to decrease with increasing cover of sagebrush for the same site productivity. Shrub loadings for desert shrub (FRES 30), SW shrub steppe (FRES 33), and shinnery (FRES 31) were assumed to be the same as for sagebrush. Herbaceous loadings were set at half of the sagebrush model for desert shrub, a third for SW shrub steppe, and the same for shinnery.

Chaparral loadings were based on data from Riggan and others (1988), Rothermel and Philpot (1973), and Firestop (1955) that most typically represent chamise.

For pinyon-juniper, surface fuel loadings were based on data from Tiedemann (1987), Young and Evans (1987), and Debano and others (1987). Crown fuels were developed from research by Chojnacky (1994), Chojnacky and Moisen (1993), and Miller and others (1981) and analysis of 2,467 stands of pinyon-juniper in Arizona and New Mexico by David Chojnacky.

The light loading fuel model represents only very open stands of pinyon-juniper. The typical and heavy loading models represent a forested condition.

**Table 9**—Fuel models for shrub and grassland ecosystems and references used in their construction.

| Type | Classification | Litter | Duff | Herbaceous S | Herbaceous T | Herbaceous A | Shrub S | Shrub T | Shrub A | References[a] |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Tons per acre | | | | | | | | |
| Desert grasslands | FRES 40 | | | 0.15 | 0.30 | 0.45 | | | | 6,9 |
| Plains grasslands | FRES 38 | | | .30 | .63 | .95 | | | | 6,9 |
| Mountain grasslands | FRES 36 | | | .45 | .95 | 1.40 | | | | 6,9 |
| Mountain meadows | FRES 37 | | | .63 | 1.25 | 1.88 | | | | 6,9 |
| Tallgrass prairie | FRES 39 | | | 1.13 | 2.25 | 3.38 | | | | 6,7,13 |
| Wet grasslands | FRES 41 | | | 2.25 | 4.50 | 6.75 | | | | 6,7 |
| Sagebrush-low | FRES 29 | 0.07 | | .23 | .45 | .90 | 1.26 | — | — | 1,6 |
| Sagebrush-moderate | FRES 29 | .11 | | .20 | .40 | .80 | — | 2.28 | — | 1,6 |
| Sagebrush-high | FRES 29 | .14 | | .18 | .35 | .70 | — | — | 3.66 | 1,6 |
| Chaparral-low | FRES 34 | .20 | 0.5 | .35 | .50 | .65 | 5.0 | — | — | 5,6,10,11 |
| Chaparral-moderate | FRES 34 | .50 | 2.0 | .07 | .10 | .13 | — | 10.0 | — | 5,6,10,11 |
| Chaparral-high | FRES 34 | .50 | 3.0 | 0 | 0 | 0 | — | — | 15.0 | 5,6,10,11 |
| Desert shrub-low | FRES 30 | .07 | | .11 | .23 | .45 | 1.26 | — | — | 1,6 |
| Desert shrub-moderate | FRES 30 | .11 | | .10 | .20 | .40 | — | 2.28 | — | 1,6 |
| Desert shrub-high | FRES 30 | .14 | | .09 | .17 | .35 | — | — | 3.66 | 1,6 |
| SW shrub steppe-low | FRES 33 | .07 | | .07 | .15 | .30 | 1.26 | — | — | 1,6 |
| SW shrub steppe-moderate | FRES 33 | .11 | | .07 | .13 | .26 | — | 2.28 | — | 1,6 |
| SW shrub steppe-high | FRES 33 | .14 | | .06 | .12 | .23 | — | — | 3.66 | 1,6 |
| Texas savannah | FRES 32 | .20 | 0.5 | .38 | 1.0 | 1.5 | 3.5 | 5.0 | 6.5 | 1,6 |
| Pinyon juniper[b] | FRES 35 | 1.0 | 9.0 | .10 | .20 | .30 | 0 | 1.3 | 2.3 | 2,3,4,8,12,14 |

[a]Authors keyed to reference number are: 1. Brown 1982, 2. Chojnacky 1994, 3. Chojnacky and Moisen 1993, 4. Debano and others 1987, 5. Firestop 1955, 6. Garrison and others 1977, 7. Hulbert 1988, 8. Miller and others 1981, 9. Redman and others 1993, 10. Riggan and others 1988, 11. Rothermel and Philpot 1973, 12. Tiedemann 1987, 13. Wright and Bailey 1982, 14. Young and Evans 1987.

[b]Litter and duff adjustment factors are: light = 0.5 and heavy = 1.5. Crown fuel for typical condition: foliage = 3.6 tons per acre and 0 to 1/4 inch branchwood = 1.8 tons per acre.

Reinhardt, Elizabeth D.; Keane, Robert E.; Brown, James K. 1997. First Order Fire Eff
Model: FOFEM 4.0, user's guide. Gen. Tech. Rep. INT-GTR-344. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 65 p.

A First Order Fire Effects Model (FOFEM) was developed to predict the direct consequences of prescribed fire and wildfire. FOFEM computes duff and woody fuel consumption, smoke production, and fire-caused tree mortality for most forest and rangeland types in the United States. The model is available as a computer program for PC or Data General computer.

Keywords: fuel, fuel consumption, duff, tree mortality, prescribed fire, smoke production

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